The Mu2e Experiment

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Fermilab Users Meeting
Batavia, IL
June 20th, 2018

Overview

- Motivation and Theory
- Experiment Overview
- Experiment Design
  - Proton Beam
  - Solenoids
  - Production and Stopping Targets
  - Tracker
  - Calorimeter
  - CRV
  - DAQ/Trigger
- Mu2e Schedule
- Mu2e II
- Summary

Motivation

- Mu2e is searching for Charged Lepton Flavor Violation (CLFV)
  - Specifically, the neutrinoless conversion of a μ^- to an e^- in the field of a nucleus:

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$

- Using the current Fermilab accelerator complex, we intend to achieve a sensitivity 4 orders of magnitude better than current limits:

Target Sensitivity:

$$R_{\mu e} = \frac{\Gamma\left[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)\right]}{\Gamma\left[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)\right]} < 6.7 \times 10^{-17} (90\% \mathrm{CL})$$

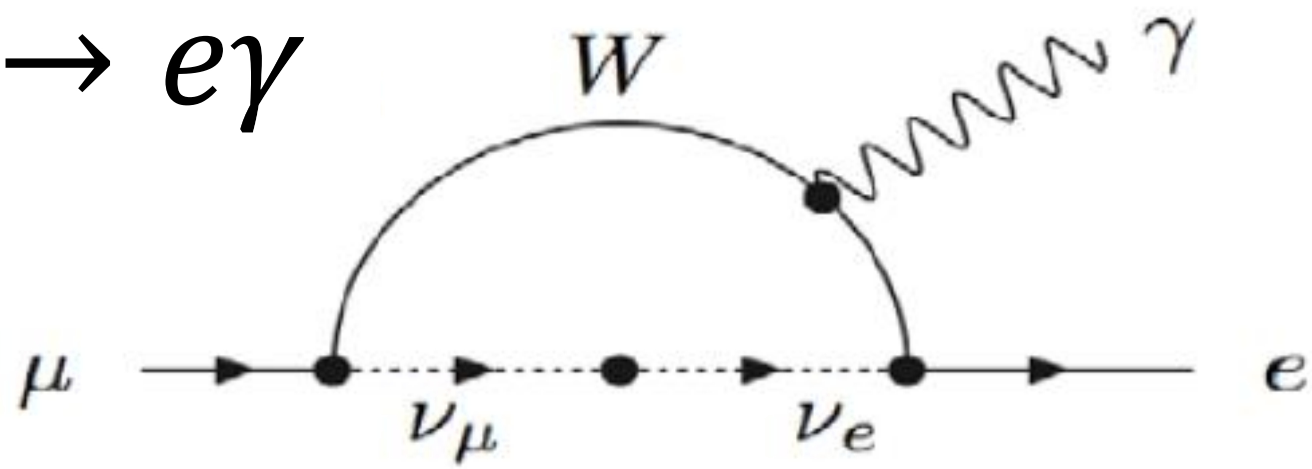
4 orders of magnitude better than current limits: **SINDRUM II [W. Bertl et al., Eur. Phys. J. C 47, 337-346 (2006)]**

- We will have discovery sensitivity over a broad range of New Physics parameter space

CLFV in the Standard Model

- CLFV is not technically allowed in the SM because since charged lepton number is accidentally conserved when neutrinos are massless
- However, if we include massive neutrinos in our model then CLFV becomes possible at the loop level due to neutrino oscillations:

$\mu \to e\gamma$



- This process is extremely suppressed:

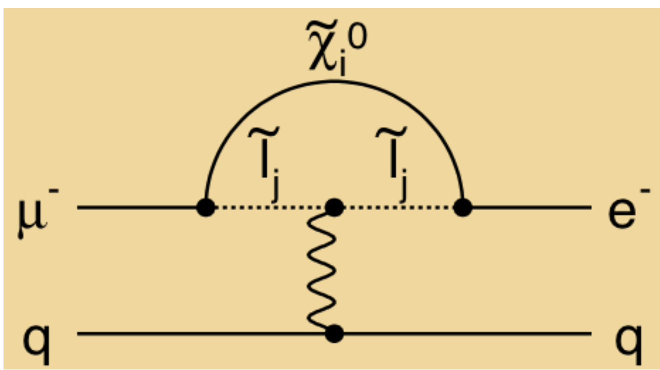
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

- Therefore, any signal at our sensitivity would be a sign of new physics

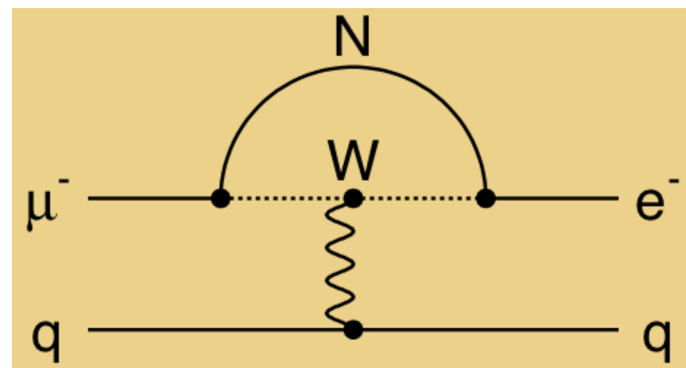
New Physics Reach

- There are many possible new physics contributions to $\mu N \to e N$, either through loops or the exchange of heavy intermediate particles
  - Many NP models predict rates observable at next gen CLFV experiments

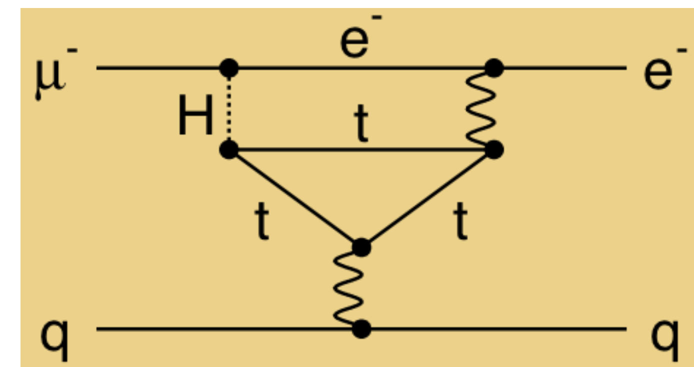
Loops



Supersymmetry

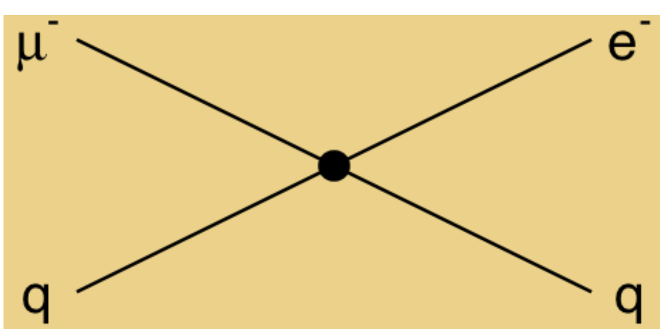


Heavy Neutrinos

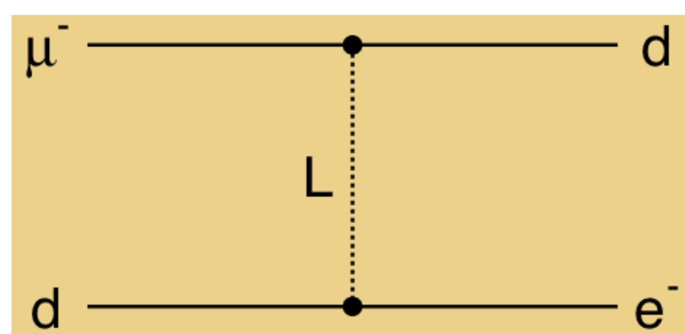


Two Higgs Doublets

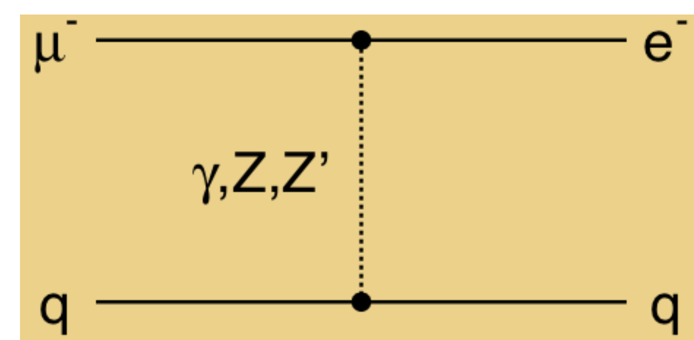
Contact Terms



Compositeness



Leptoquarks



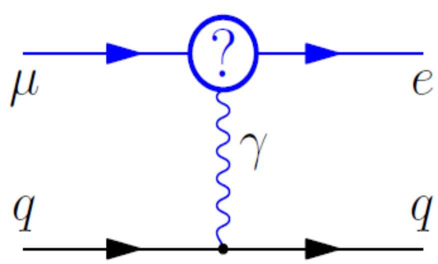
New Heavy Bosons / Anomalous Couplings

Model-Independent Effective Lagrangian

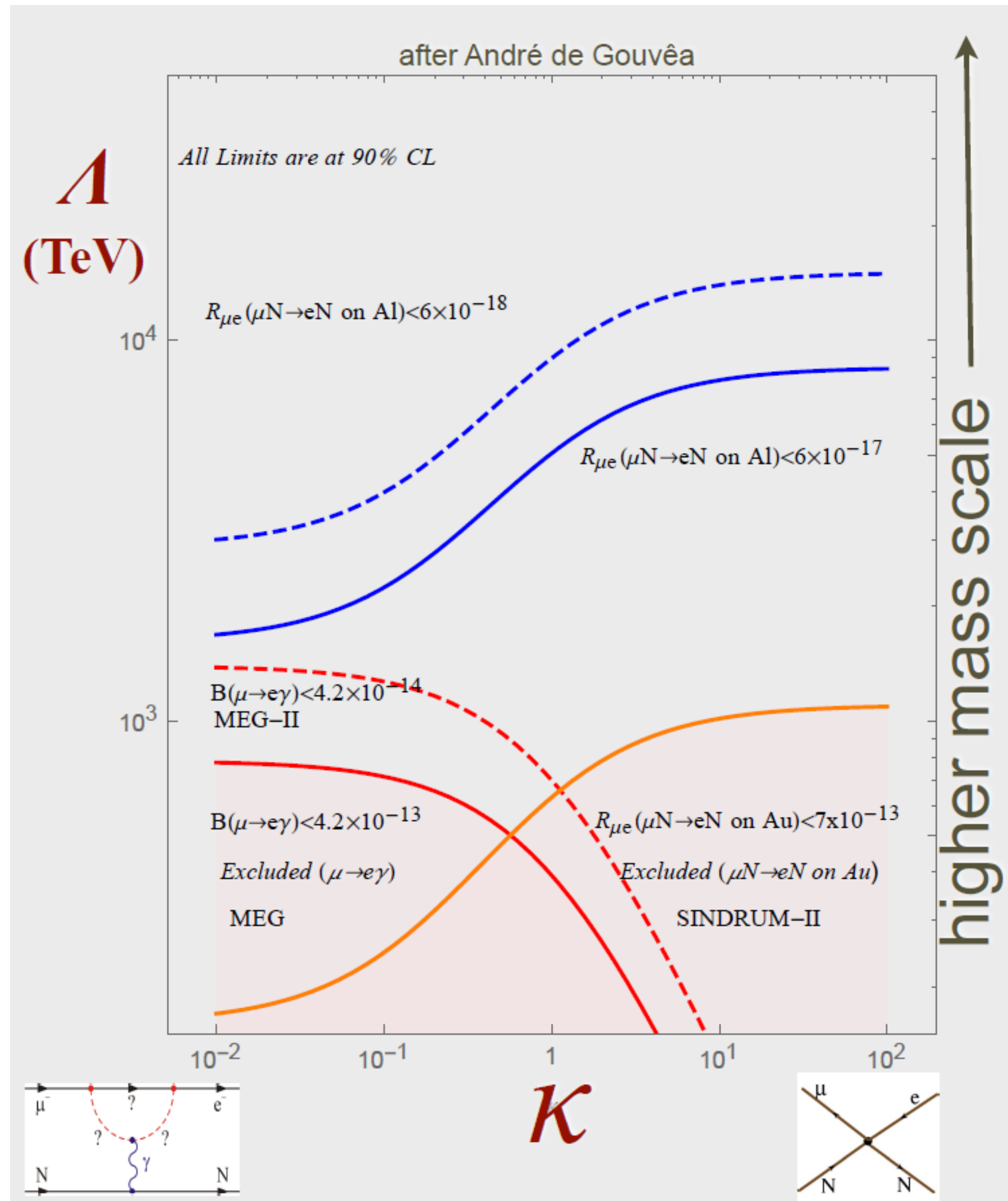
$$L_{\text{CLFV}} = \frac{m_m}{(1+k)\Lambda^2}\bar{m}_R s_{mn} e_L F^{mn} \quad + \quad \frac{k}{(1+k)\Lambda^2}\bar{m}_L g_m e_L(\bar{u}_L g_m u_L + \bar{d}_L g_m d_L) \quad + h.c.$$

Λ: effective mass scale of New Physics k: relative contribution of the contact term

"Dipole term"

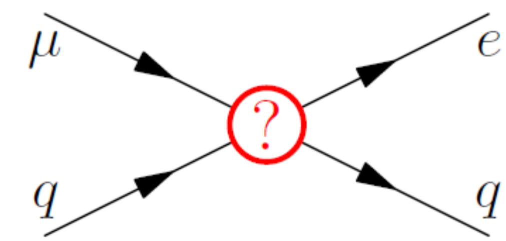


Contributes to $\mu \to e\gamma$



Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

"Contact term"

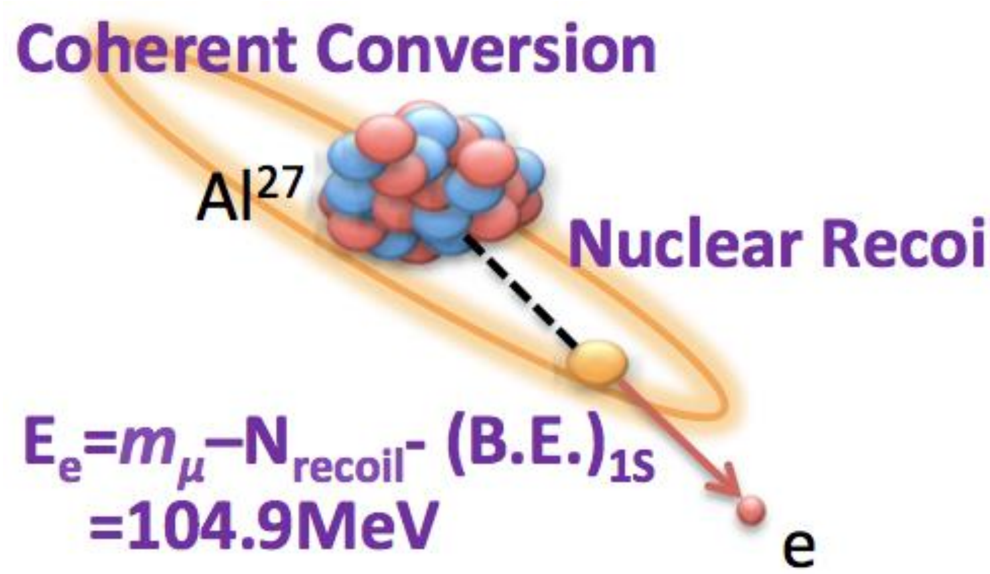


No contribution to $\mu \to e\gamma$

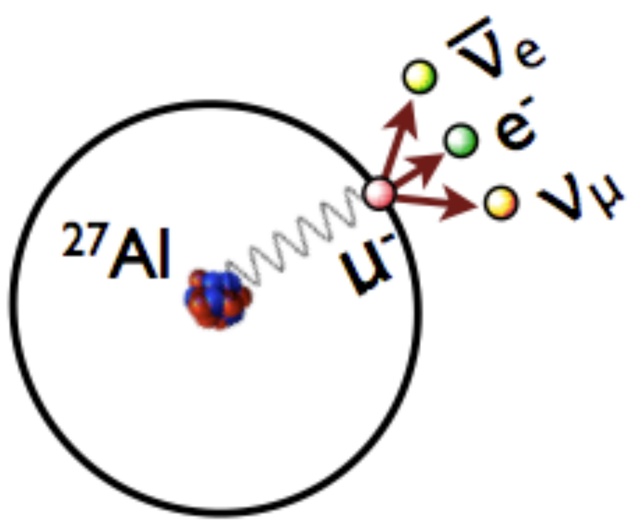
- CLFV can probe very high mass scales O(1000 – 10,000 TeV)

Experimental Concept

- Generate a beam of low momentum muons
  - Muons are stopped in an aluminum target
  - When stopped muons convert to electrons, the nucleus recoils and the electron is emitted at a specific energy



- Signal is mono-energetic electron at 104.9 MeV
  - Main intrinsic background is Decay In Orbit (DIO) events

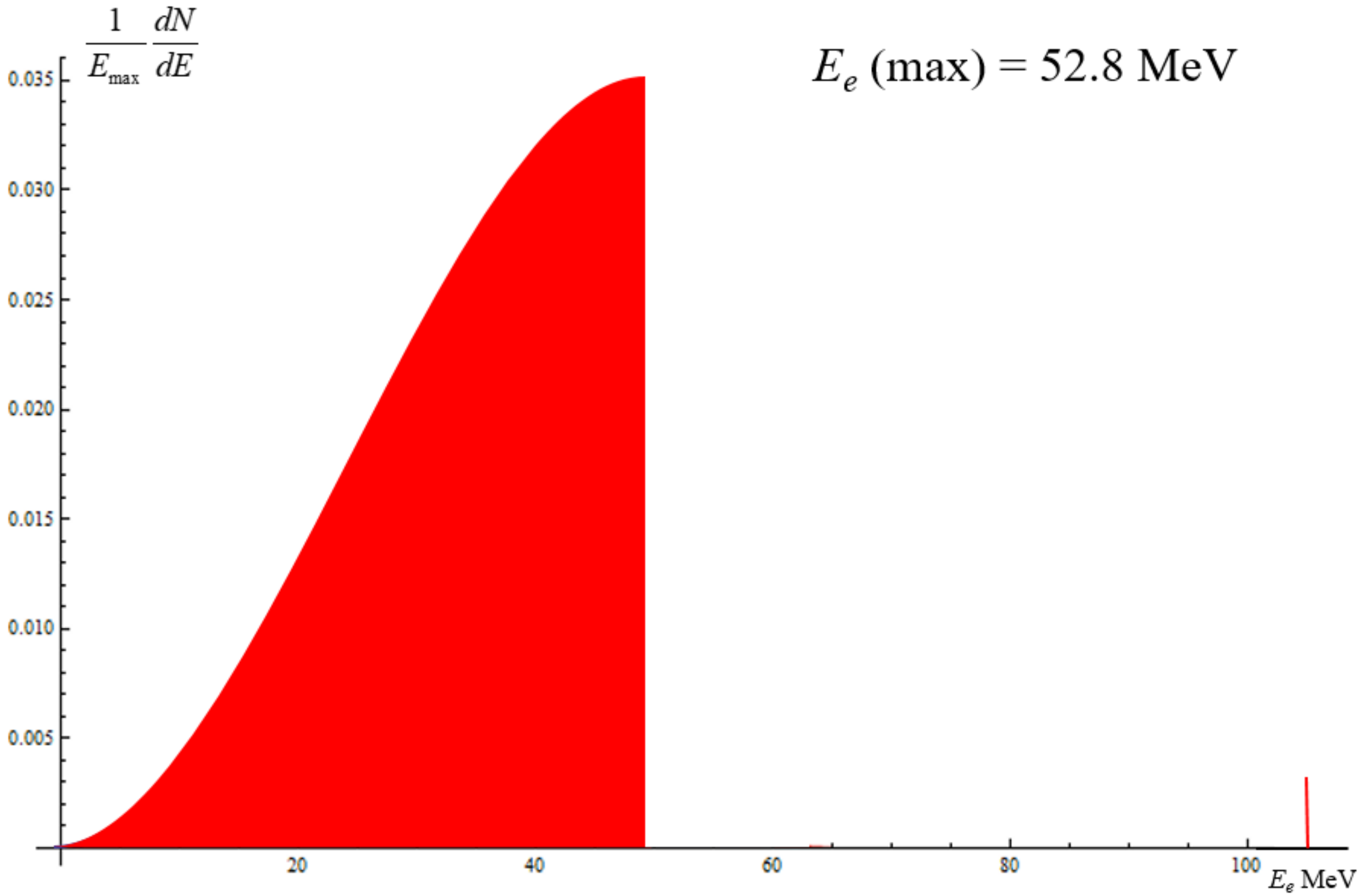


Decay In Orbit

- To achieve our target sensitivity, we need $\sim 10^{18}$ stopped muons over 3 year run
  - => $\sim 10^{10}$ stopped muons per second

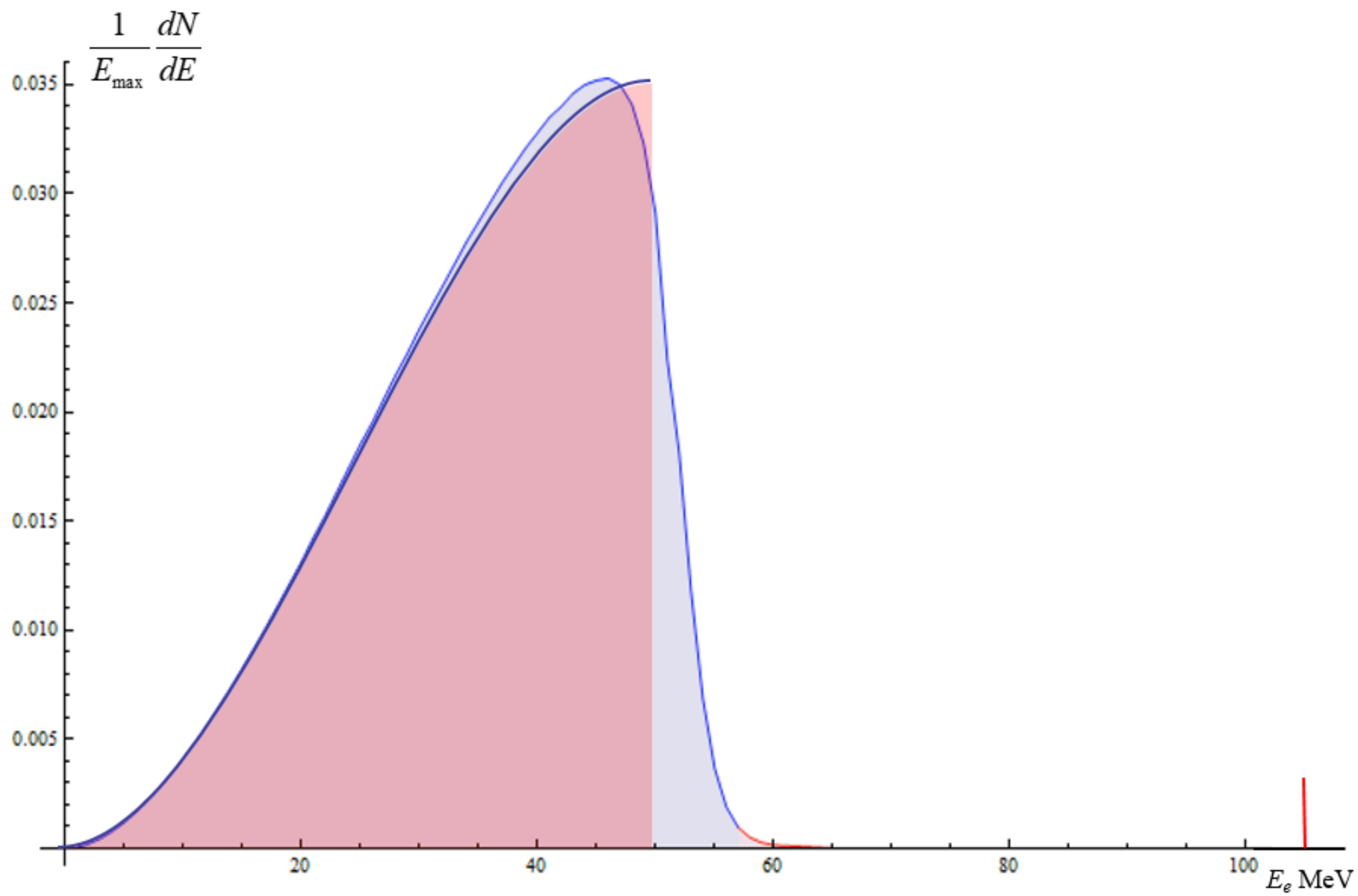
Decay In Orbit Energy Distribution

- Although the maximum electron energy from free muon decay is far below our signal energy (104.9 MeV)…



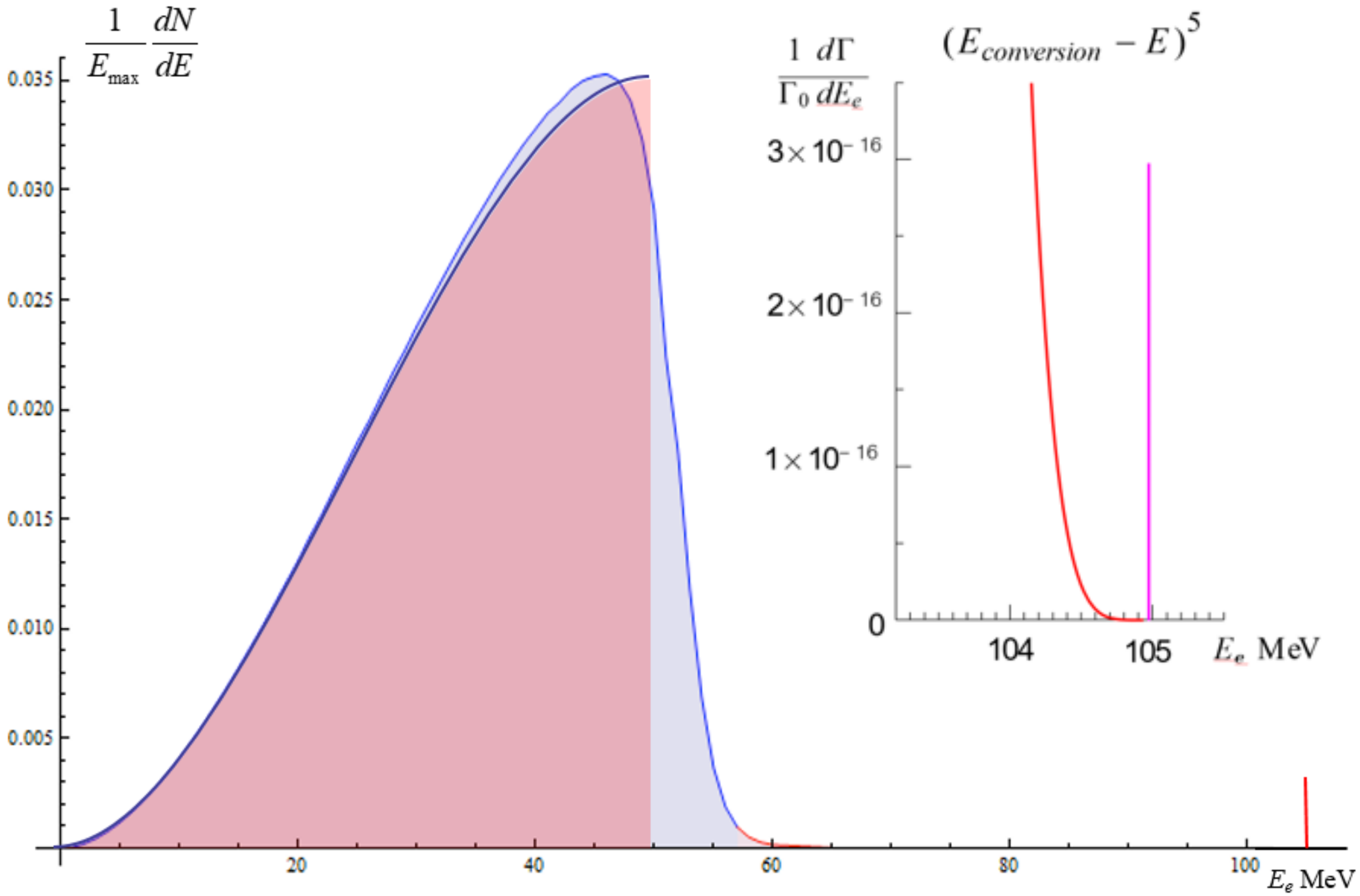
Decay In Orbit Energy Distribution

- The decay spectrum is distorted by the presence of the nucleus…



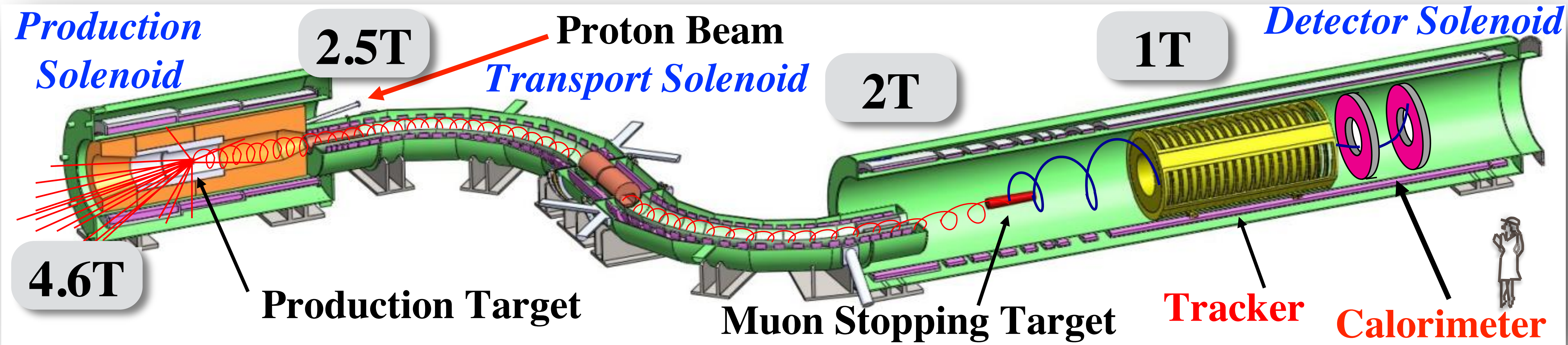
Decay In Orbit Energy Distribution

- …so the maximum energy for the DIO electrons can come very close to the signal energy:

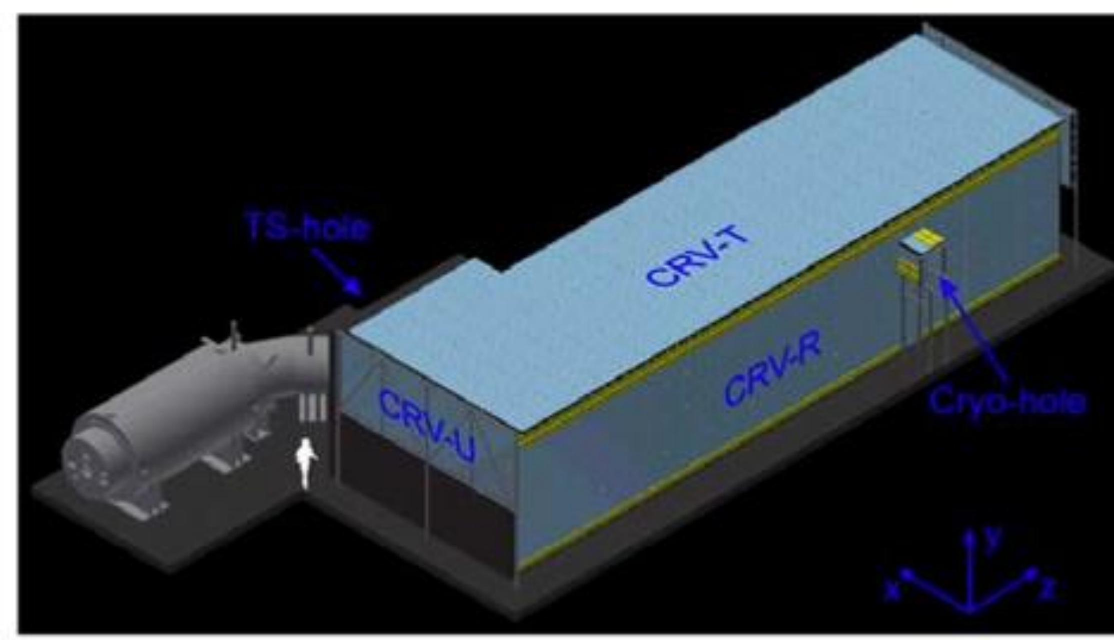


- Therefore, it is important that we have good energy resolution

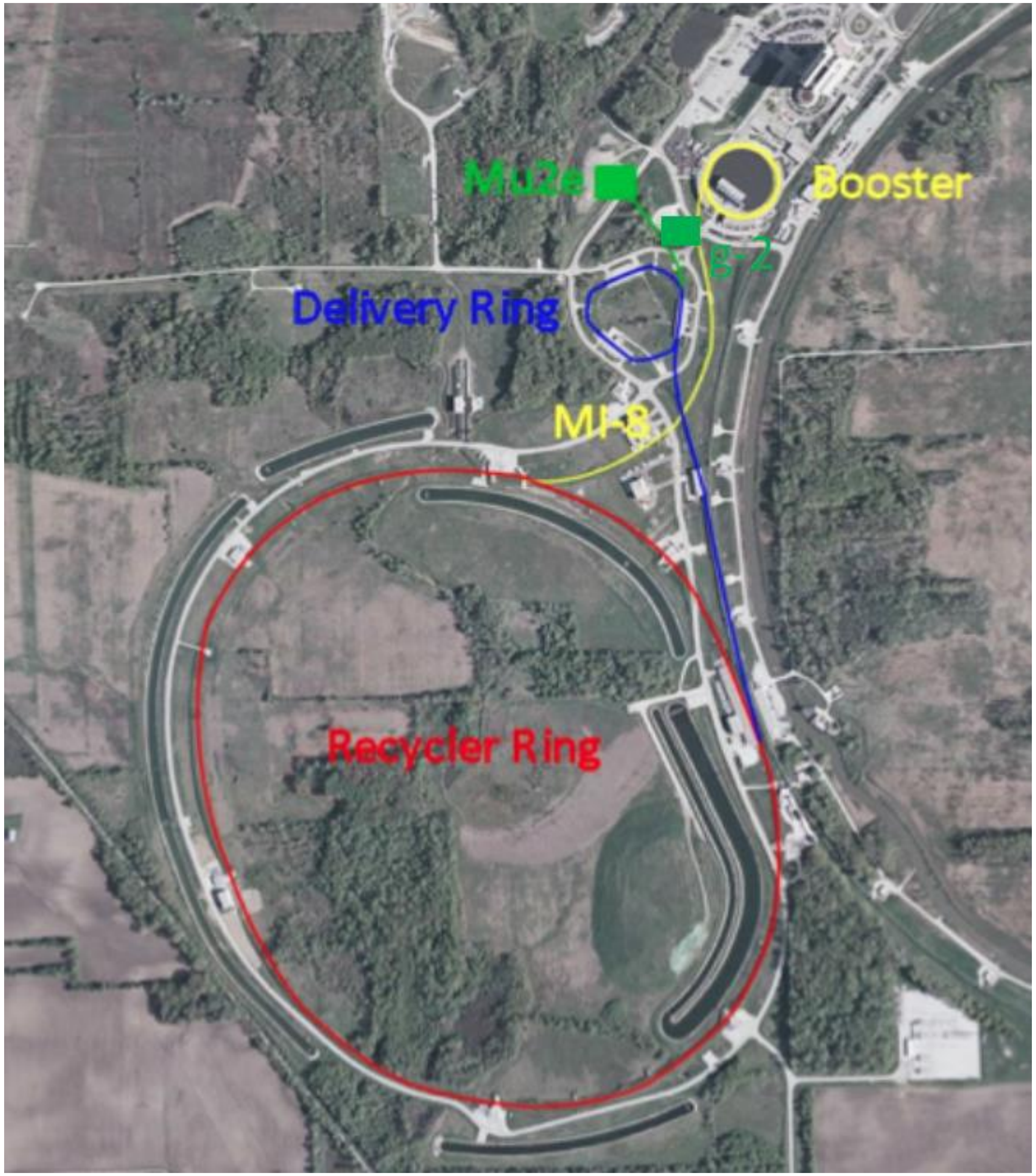
Design Overview



- Production Target + Production Solenoid
  - High intensity, pulsed, 8 GeV proton beam strikes tungsten production target producing pions
  - Pions are captured by the graded magnetic field and decay to muons
- Transport Solenoid
  - Selects low momentum, negative muons
  - Absorbers and Collimators eliminate high energy negative particles, positive particles, and line-of-sight neutrals
- Stopping Target, Detector, and Detector Solenoid
  - Muons are stopped on an aluminum target
  - Tracker measures momentum and trajectories of electrons from muonic atoms
  - Calorimeter measures energy/time
- Cosmic Ray Veto detector surrounds detector solenoid



The Mu2e Proton Beam



- Mu2e will take advantage of the existing Booster, Recycler, Accumulator, and Antiproton Source Debuncher rings at Fermilab
- Mu2e will run in parallel with NOvA
- Mu2e cannot be simultaneously run with g-2, but could run after g-2 or alternate with it

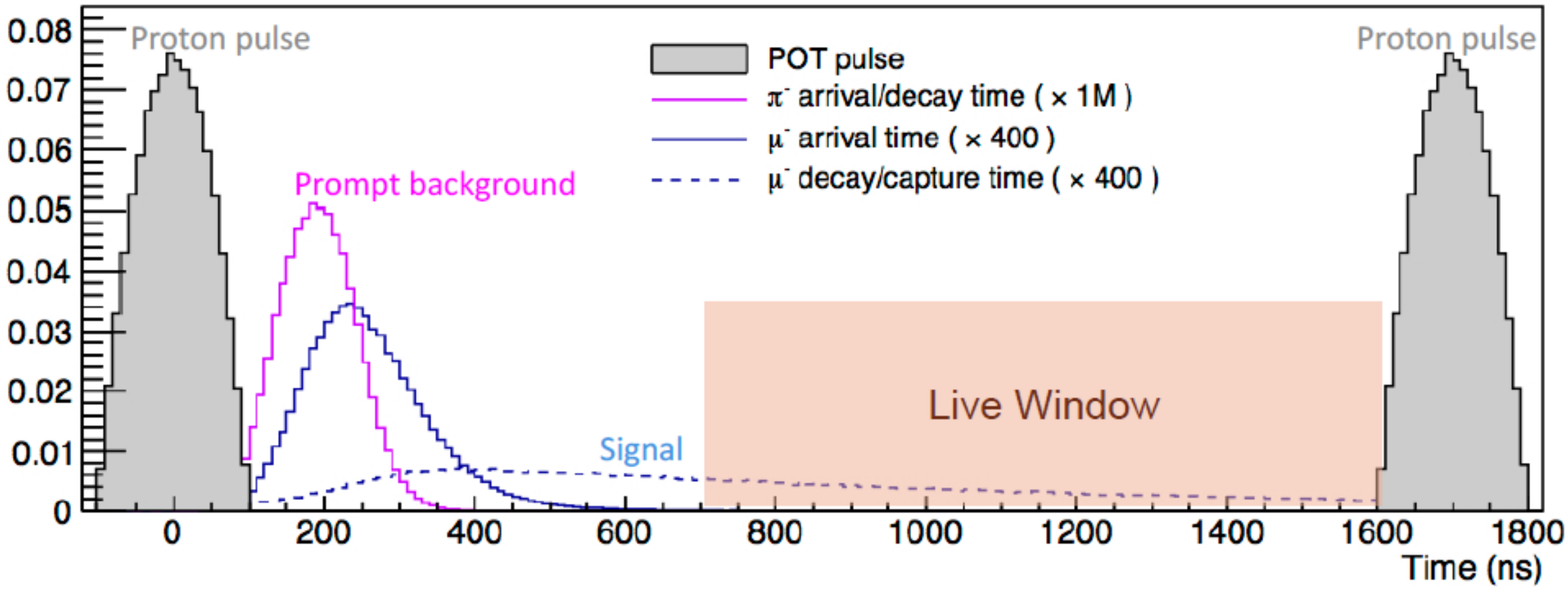
Radiative Pion Capture

- As previously described, we generate pions in order to make muons
  - However, sometimes the pions live long enough to reach the stopping target
- Pions arriving at the stopping target can undergo radiative pion capture (RPC):
  - $\pi N \rightarrow N'\gamma, \quad \gamma \rightarrow e^+e^-$
  - $\pi N \rightarrow N'e^+e^-$

  potentially producing an electron at the signal energy
- In order to suppress this background, we use a pulsed beam structure with a delayed data-taking window

Proton Pulse Structure

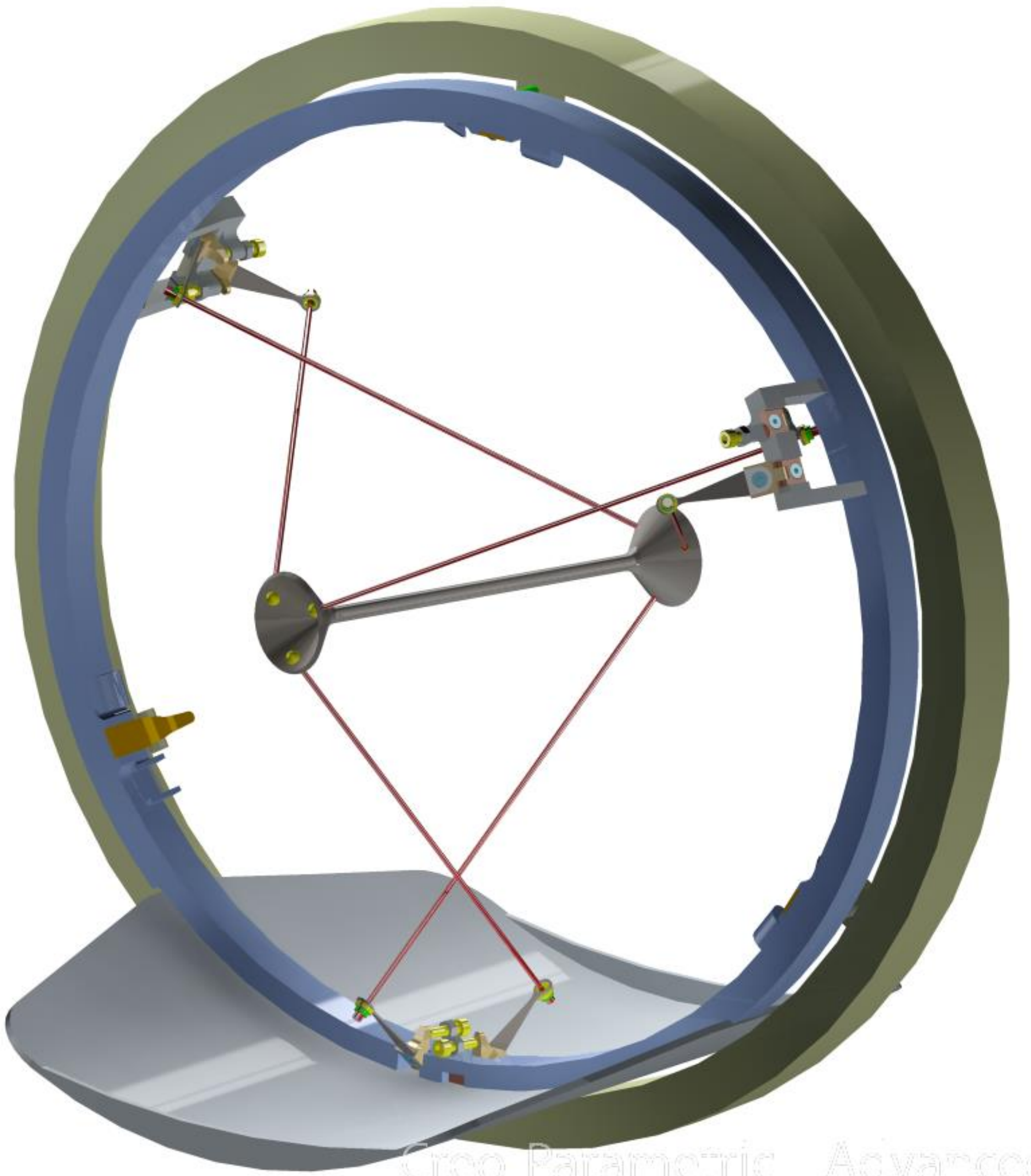
- Proton Pulse Structure:



  - We wait for the "prompt" pion backgrounds to subside before opening the live window
  - A 700 ns delay reduces pion background by $> 10^{-11}$
- We need a 10^{-10} out-of-pulse/in-pulse proton ratio (extinction)
  - This "extinction ratio" is measured and monitored throughout the experiment

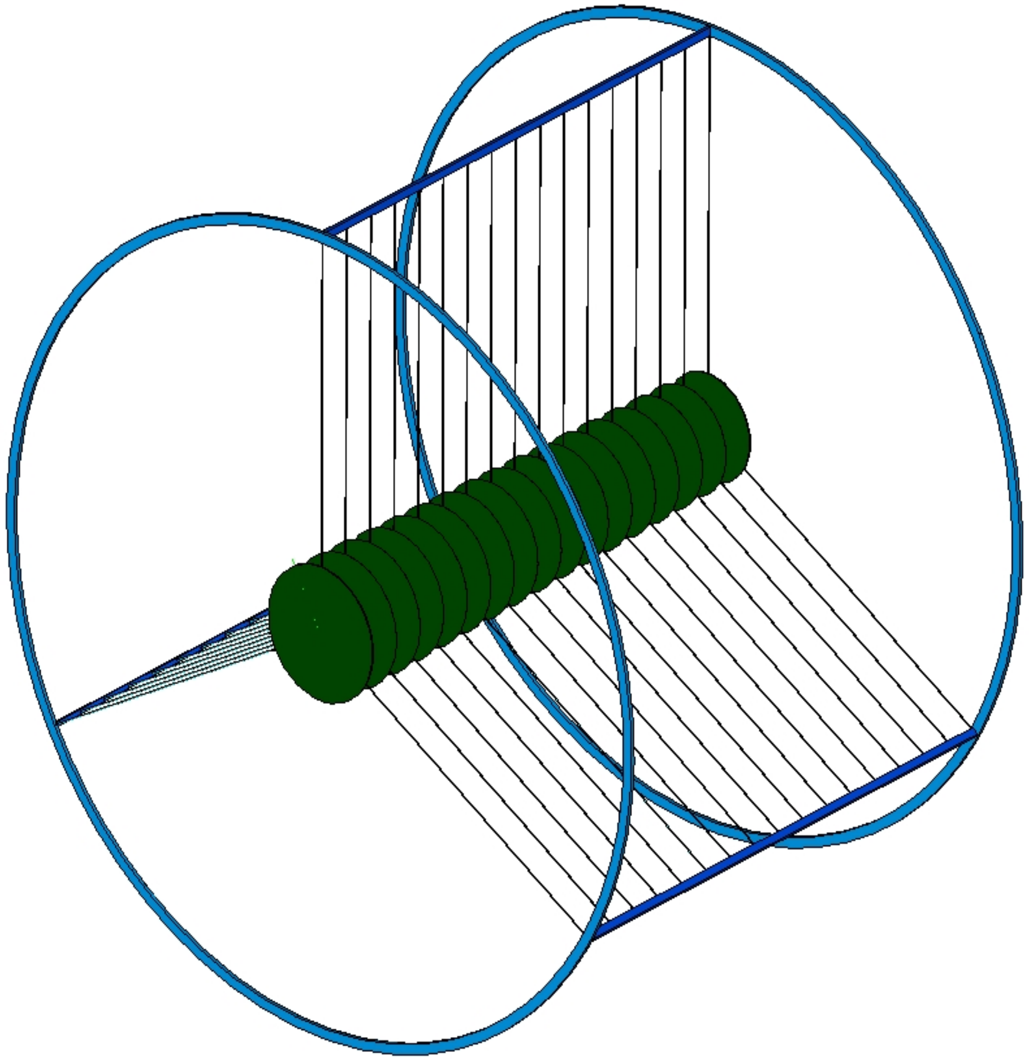
Production Target

- Production Target
  - Radiatively cooled tungsten target suspended by wires
  - Produces pions when struck by the proton beam
  - Muons are guided to the stopping target by the production and transport solenoids



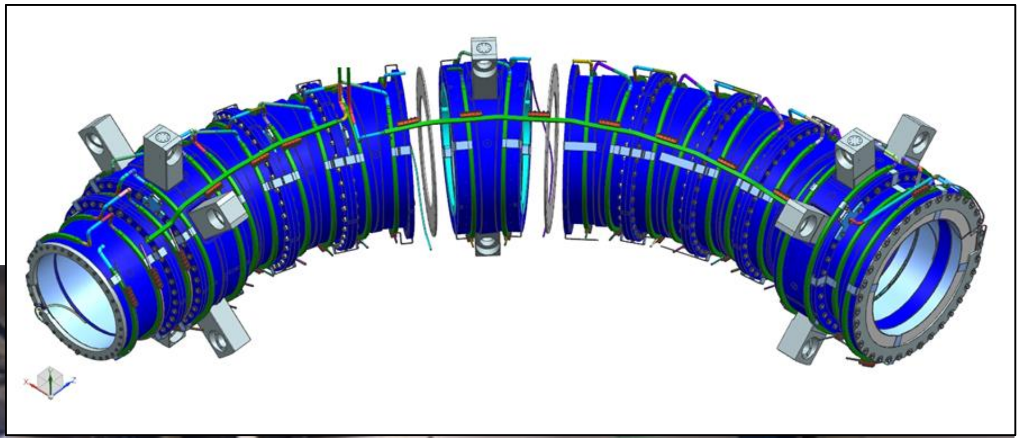
Stopping Target

- Stopping Target
  - Aluminum stopping target composed of foils suspended by wires
  - If a signal is seen, other stopping target materials may be used to narrow down what kind of physics is responsible
  - Design is still being optimized, but it will probably consist of something like aluminum foil annuli suspended at intervals in a cylindrical volume



Solenoid Status

- Solenoid production is underway
  - All superconducting cables for solenoids have been manufactured
  - A production module for the transport solenoid (TS) have been constructed and cold tests are being performed
  - Warm bores for the production and detector solenoid have been delivered to General Atomics



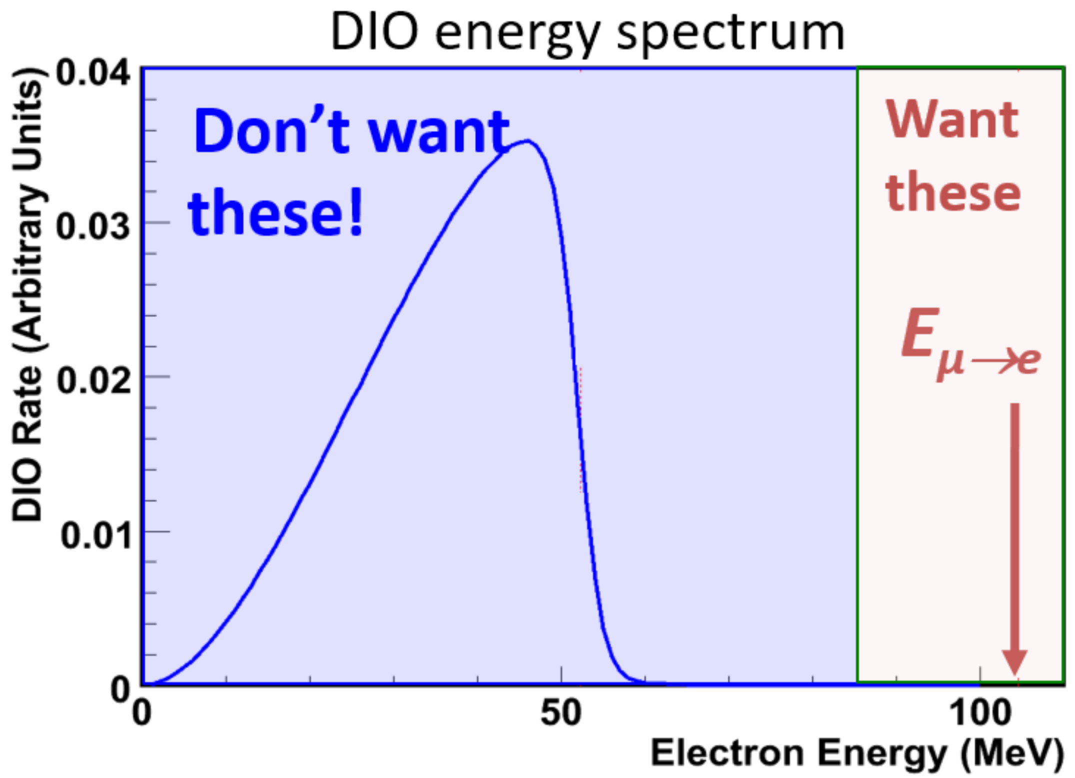
Solenoid Status II

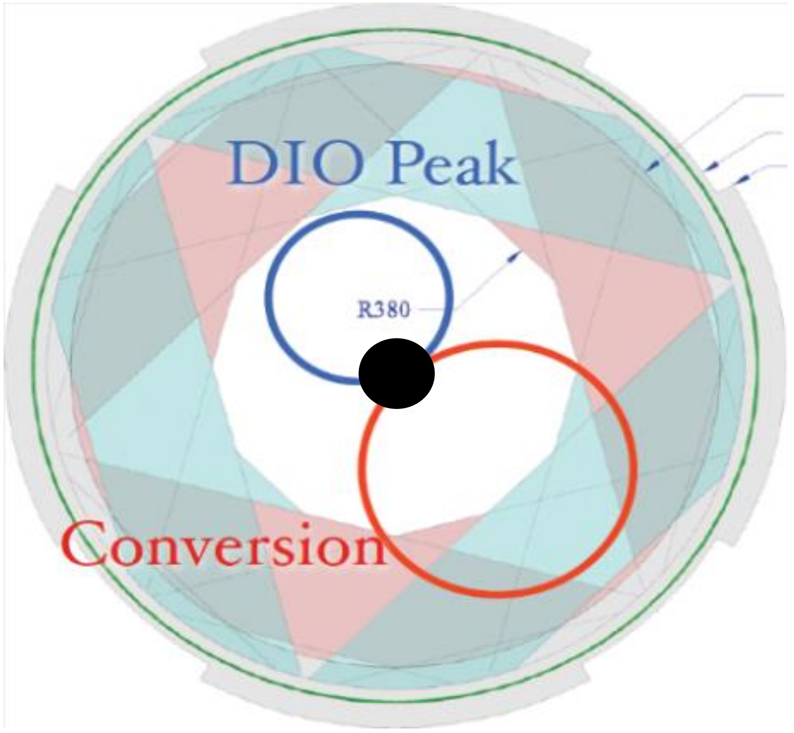
- Warm Bores en route to Tupelo, MS




Tracker I

- A low-mass annular tracker provides us with high-precision measurements of charged particle momenta
  - Designed to function in a high background environment
  - Within the detector solenoid, track radius is proportional to transverse momentum so we use an annular design that only detects particles with large enough radii



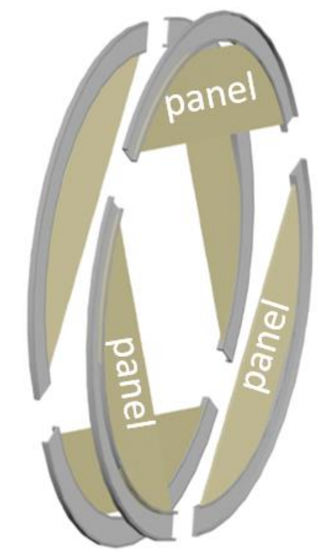


  - Expect < 180 keV/c p_T resolution at 105 MeV/c (< 0.18%)

Tracker II

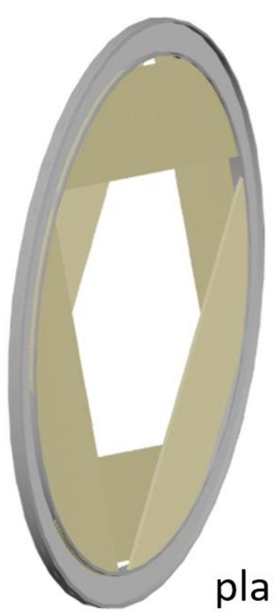
- Tracker Construction:
  - Tracker is constructed from self-supporting panels of low mass straws tubes detectors:

- 5 mm diameter straw
- Spiral wound
- Walls: 12 mm Mylar + 3 mm epoxy + 200 Å Au + 500 Å Al
- 25 mm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO2 with HV < 1500 V

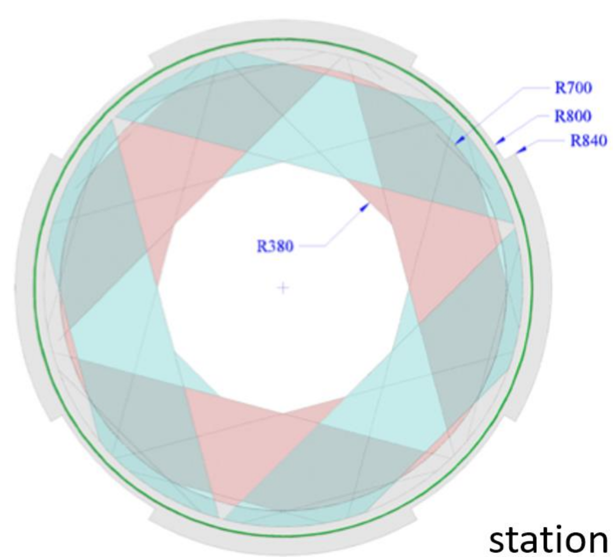


96 straws/panel

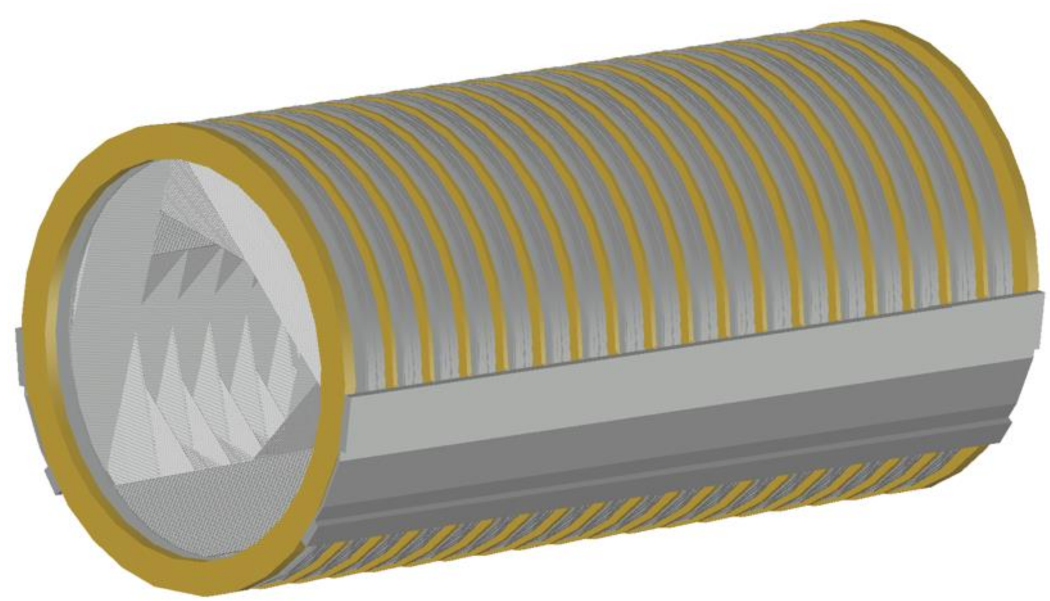
  - Sets of 6 panels are attached to form a plane, 2 planes are combined to form a station, and 18 stations are arranged in a cylindrical volume to form the tracker:



6 panels/plane



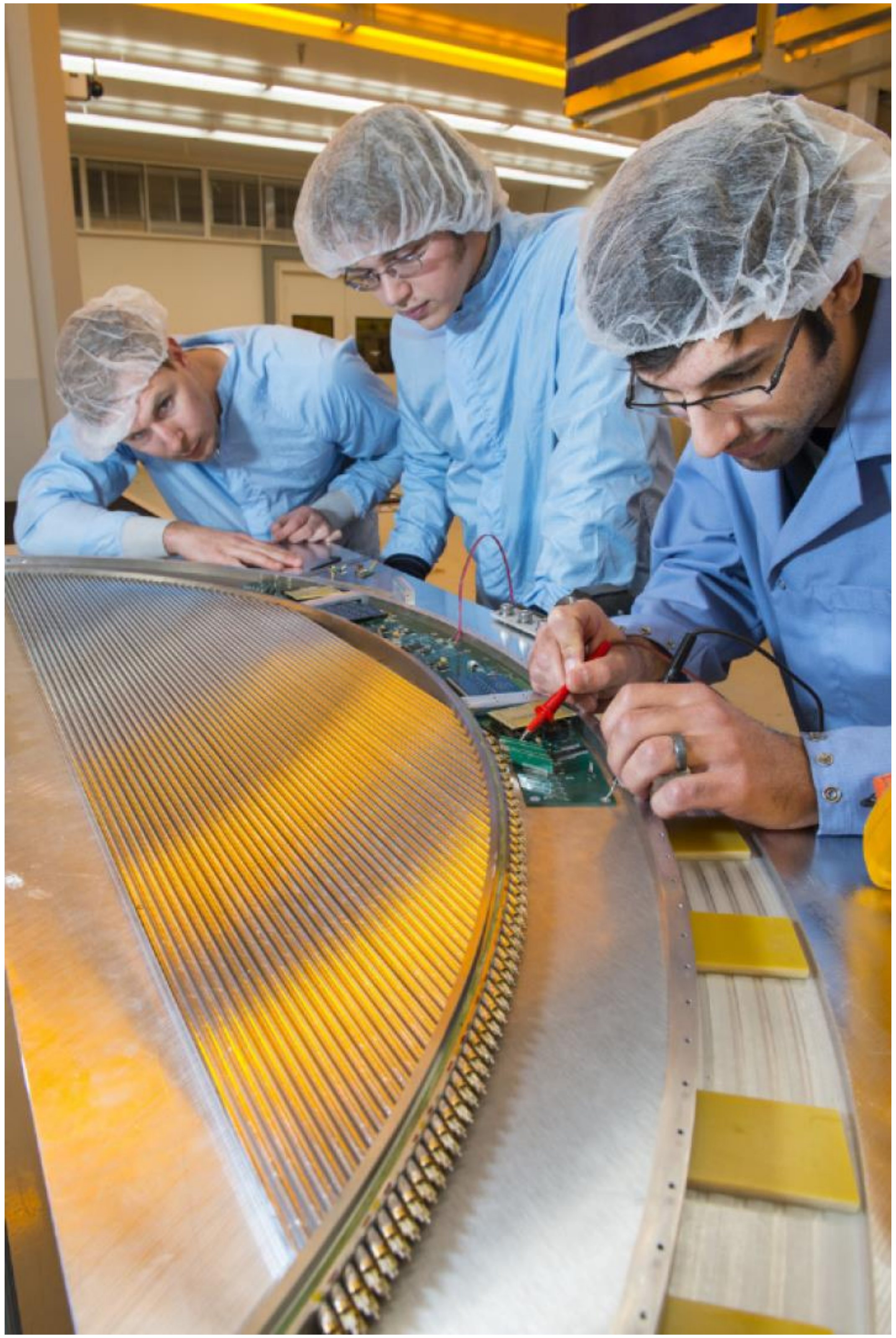
2 panels/station

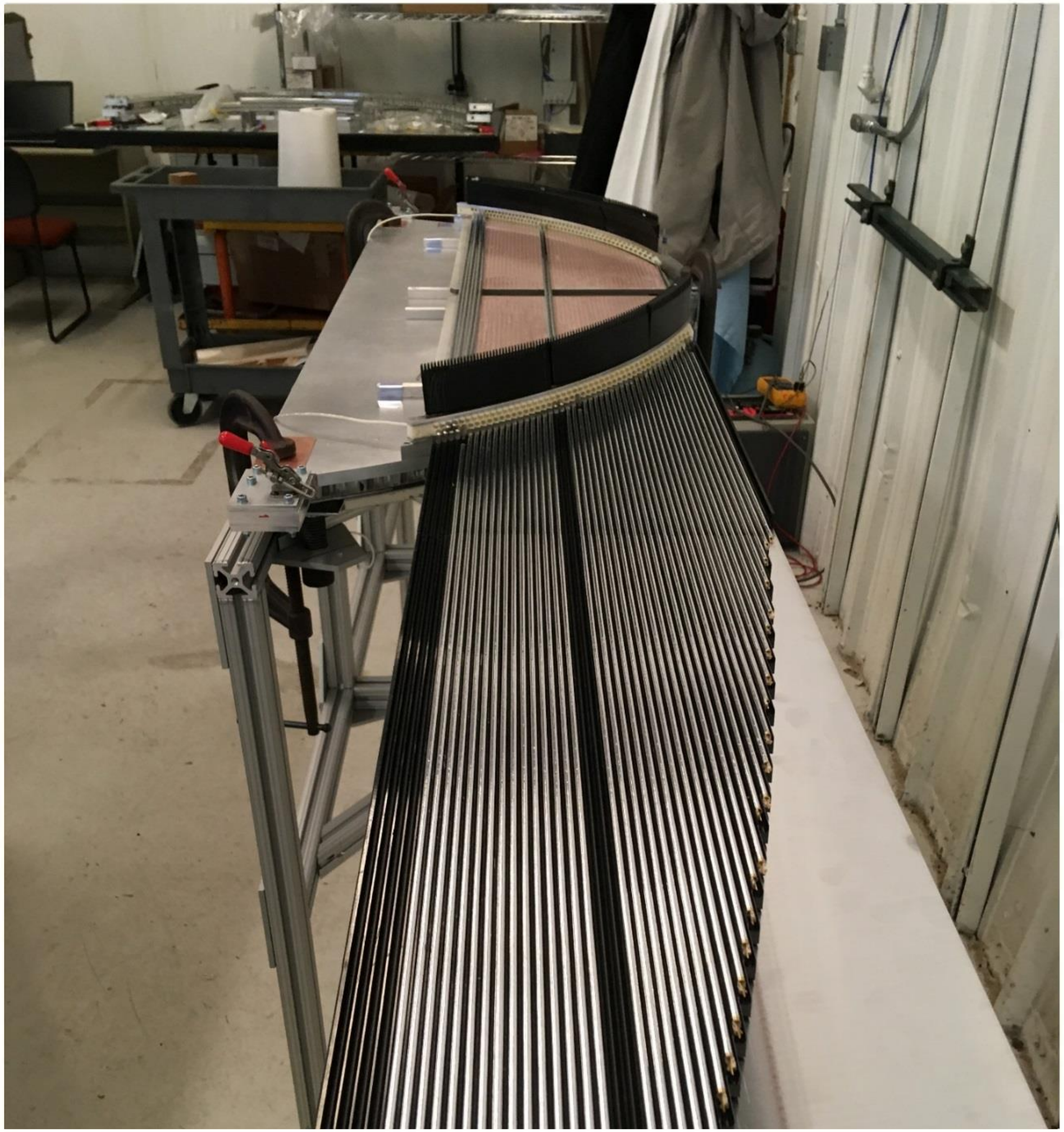


18 station tracker

Tracker III

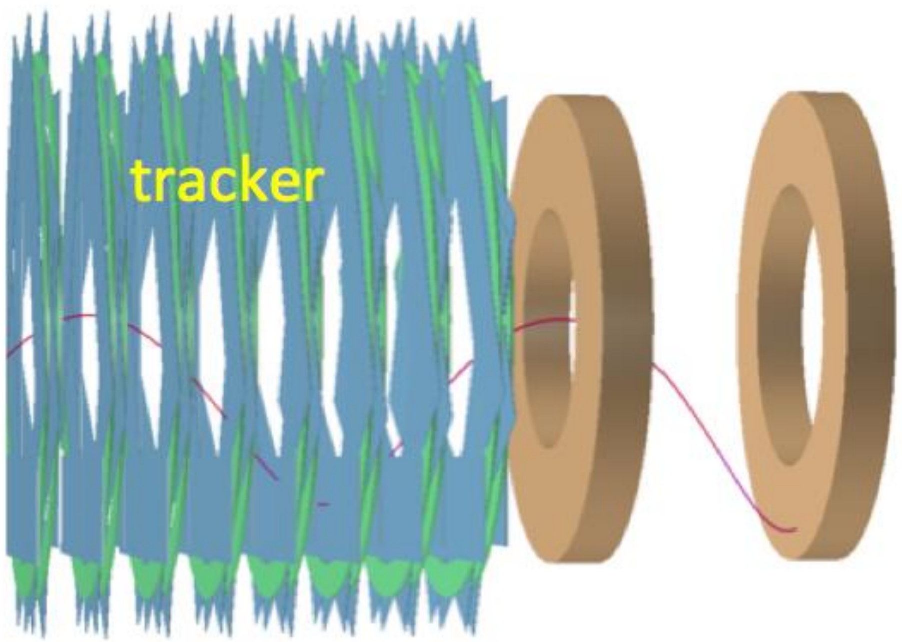
- Tracker Construction:



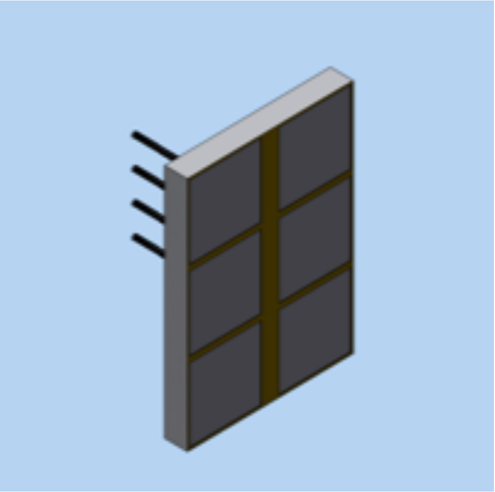


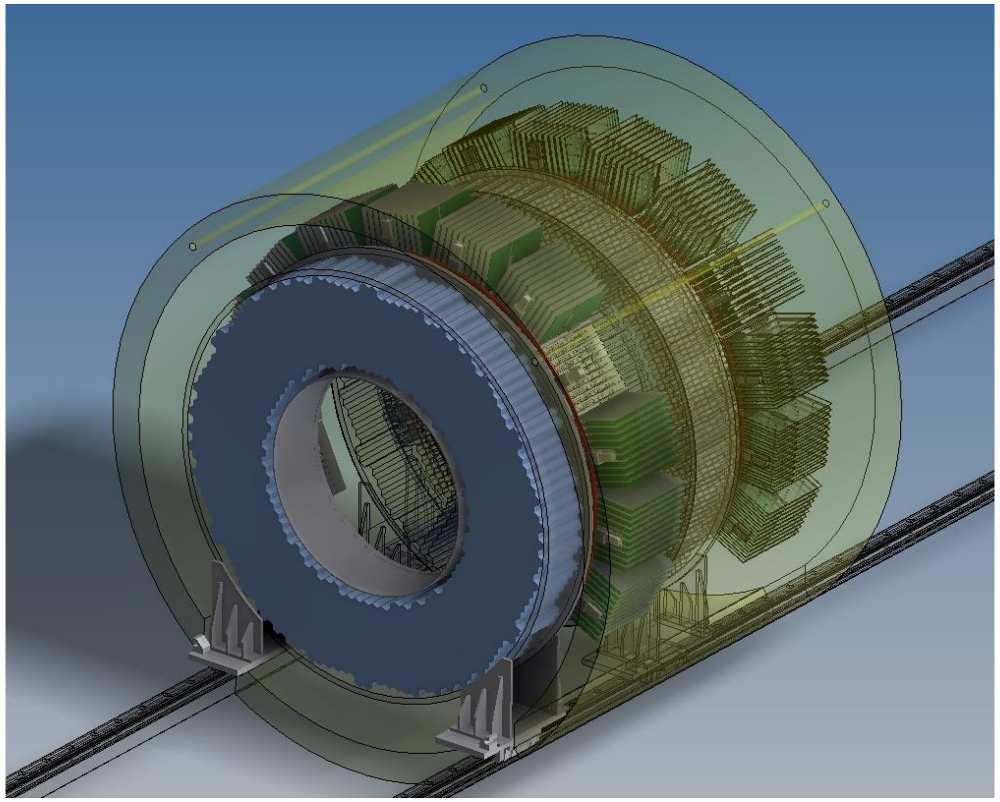
Calorimeter I

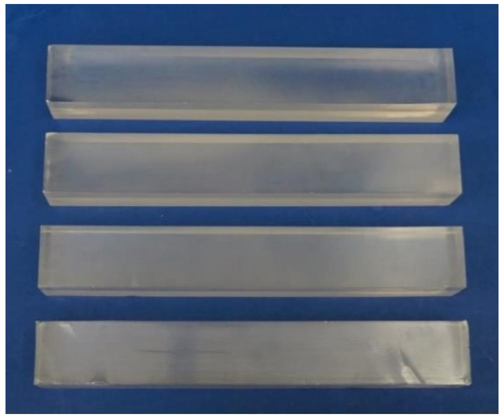
- Calorimeter Serves to
  - Distinguish muons from electrons
  - Aid in track pattern recognition
  - Provide tracker-independent trigger
  - Provide accurate timing information for bkg rejection

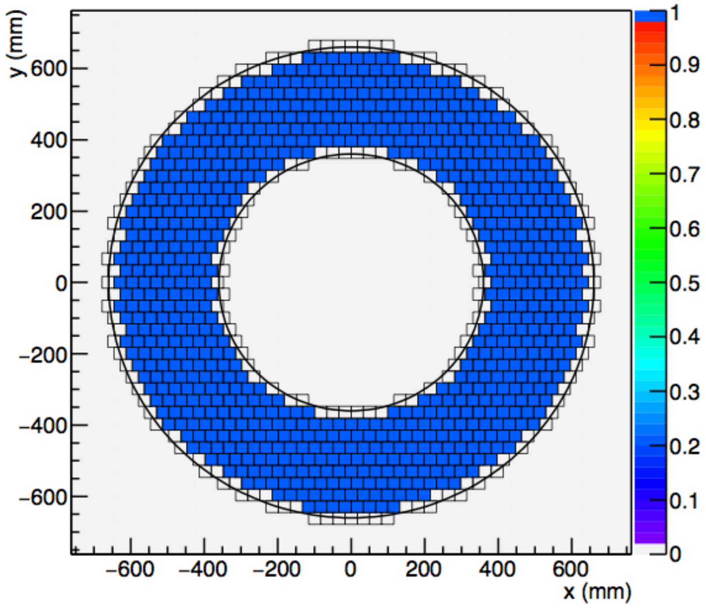


- Calorimeter Design:
  - Two annuli with radius 37-66 cm
  - Disks separated by 70 cm (1/2 λ)
  - ~674 CsI crystals per disk
  - Two 14x20 mm^2 six-element SiPMs / crystal
  - Square crystals (34x34x200 mm^3)



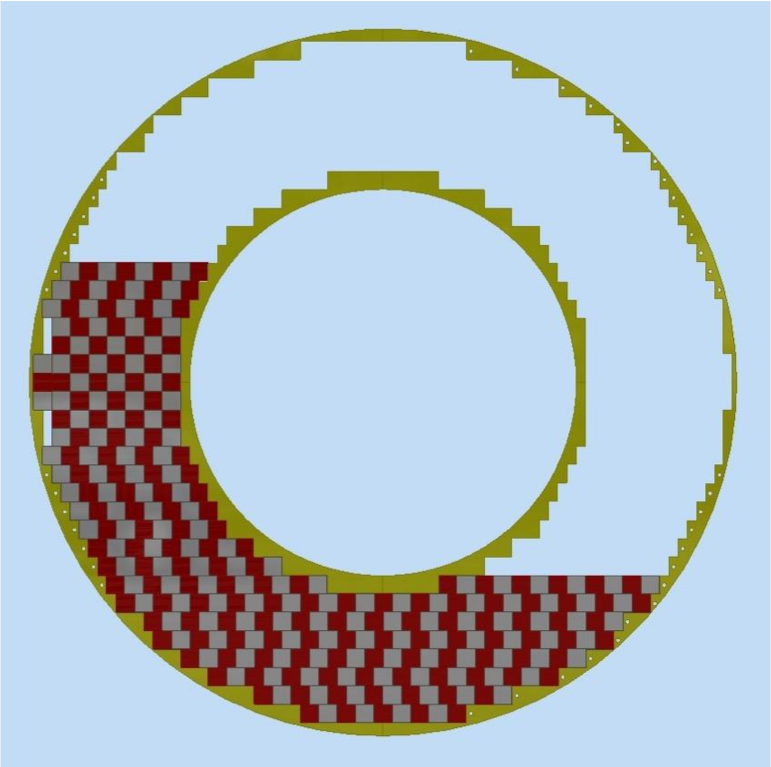




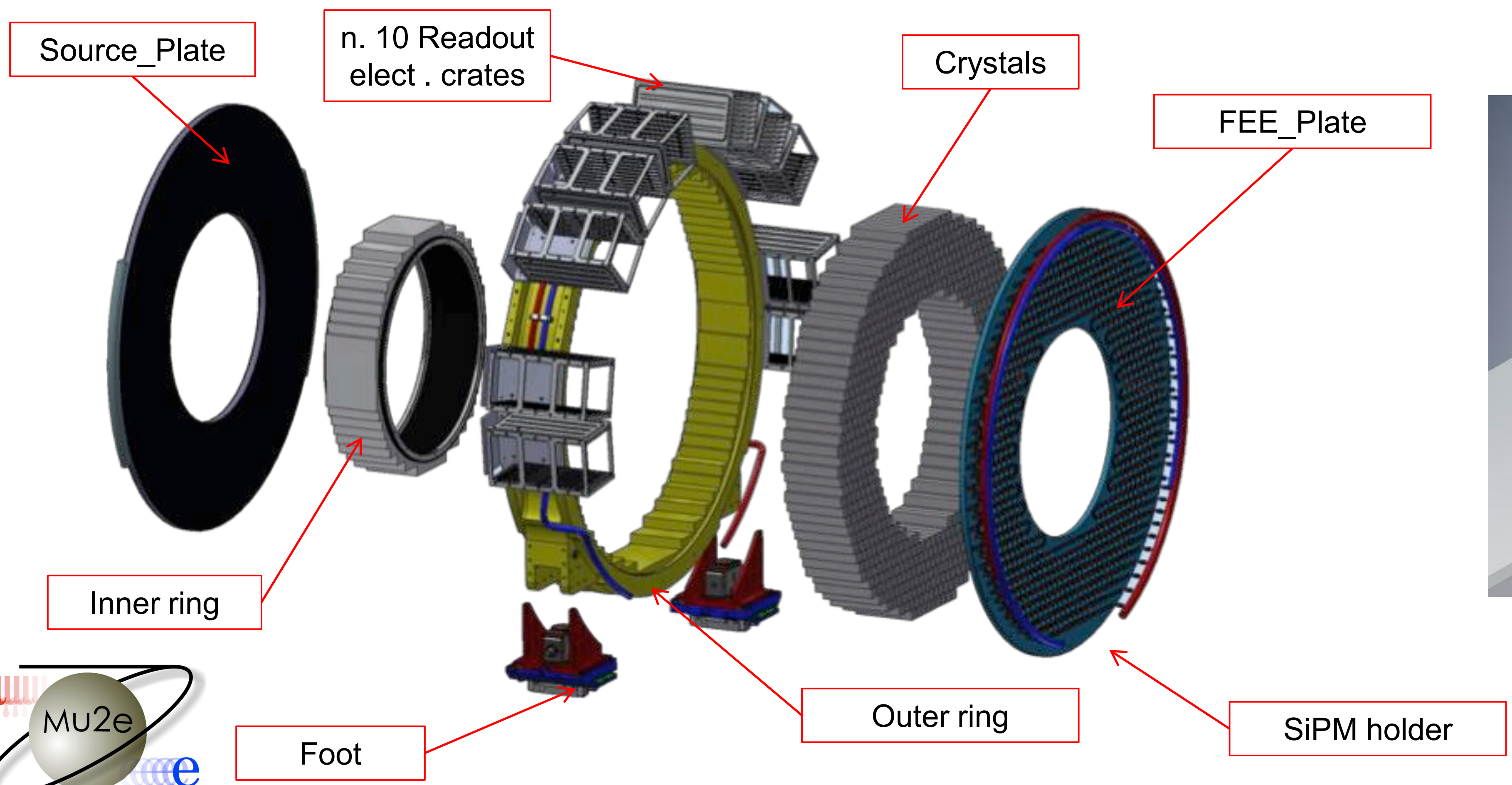


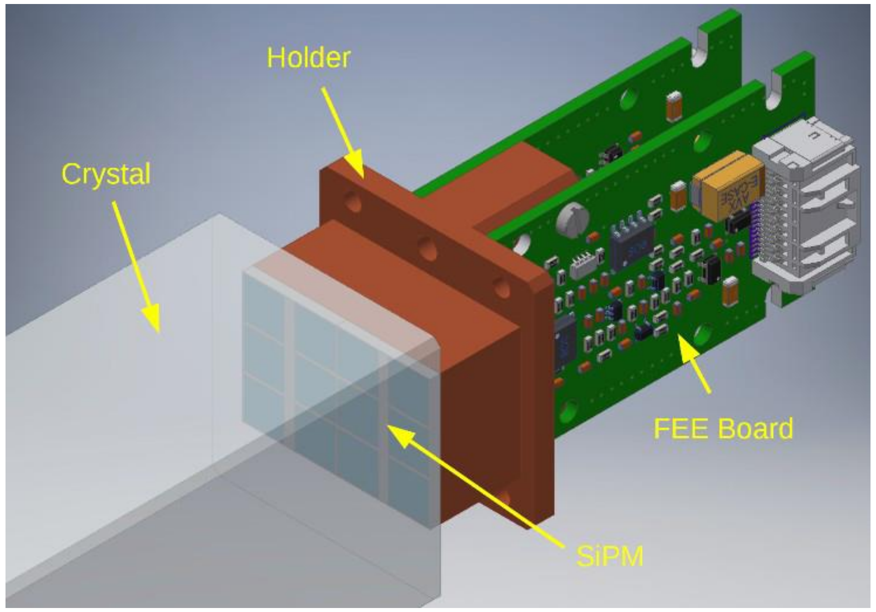
Calorimeter II

- Wrap crystals in Tyvek and stack in annulus
- A backplane assembly provides cooling and slots mounting crystal readout electronics
  - Insert SiPM holders with front end electronics (FEE) into the backplane (air-gap coupling)
  - FEE are read out by readout controllers housed in crates



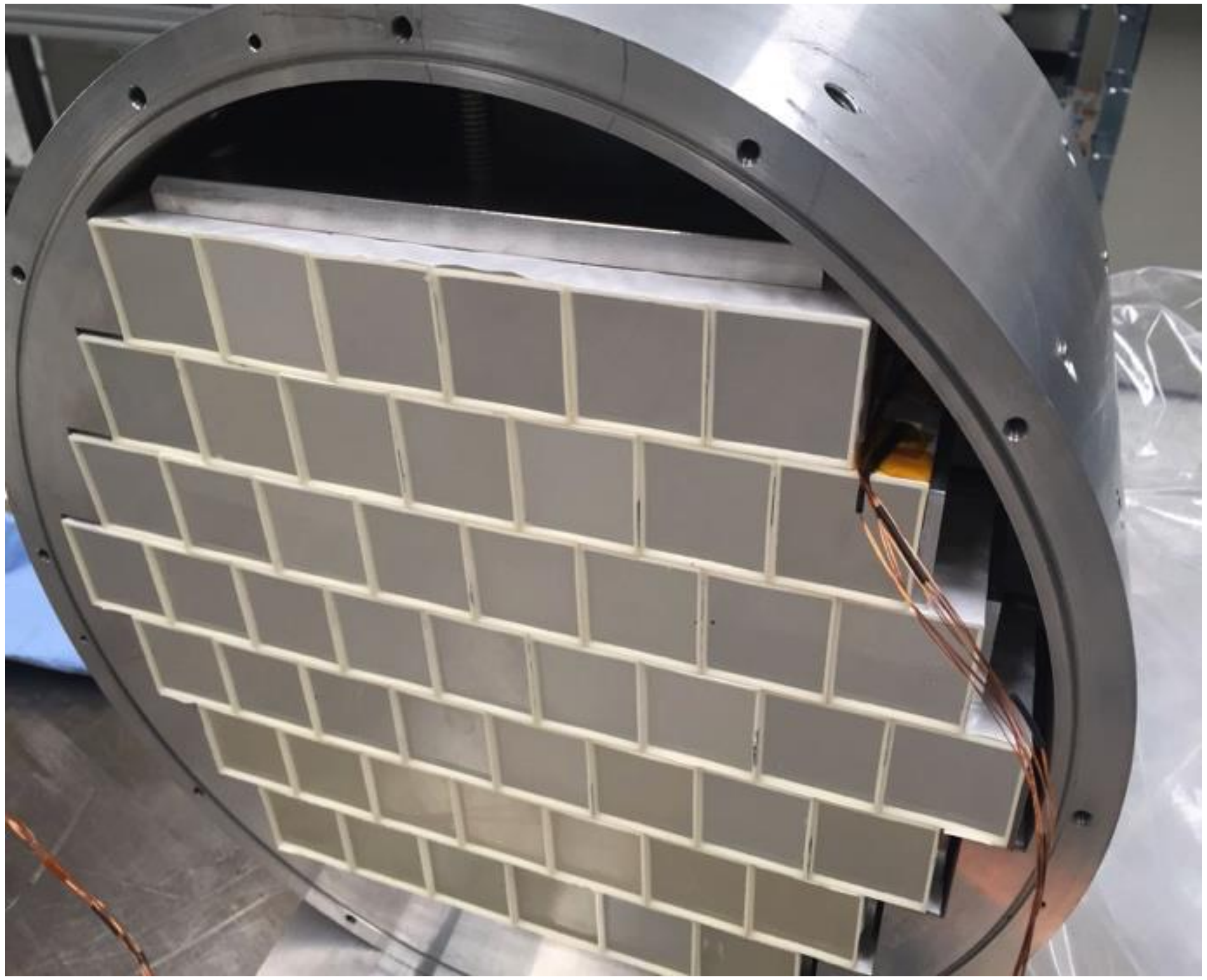
Crystal Stacking

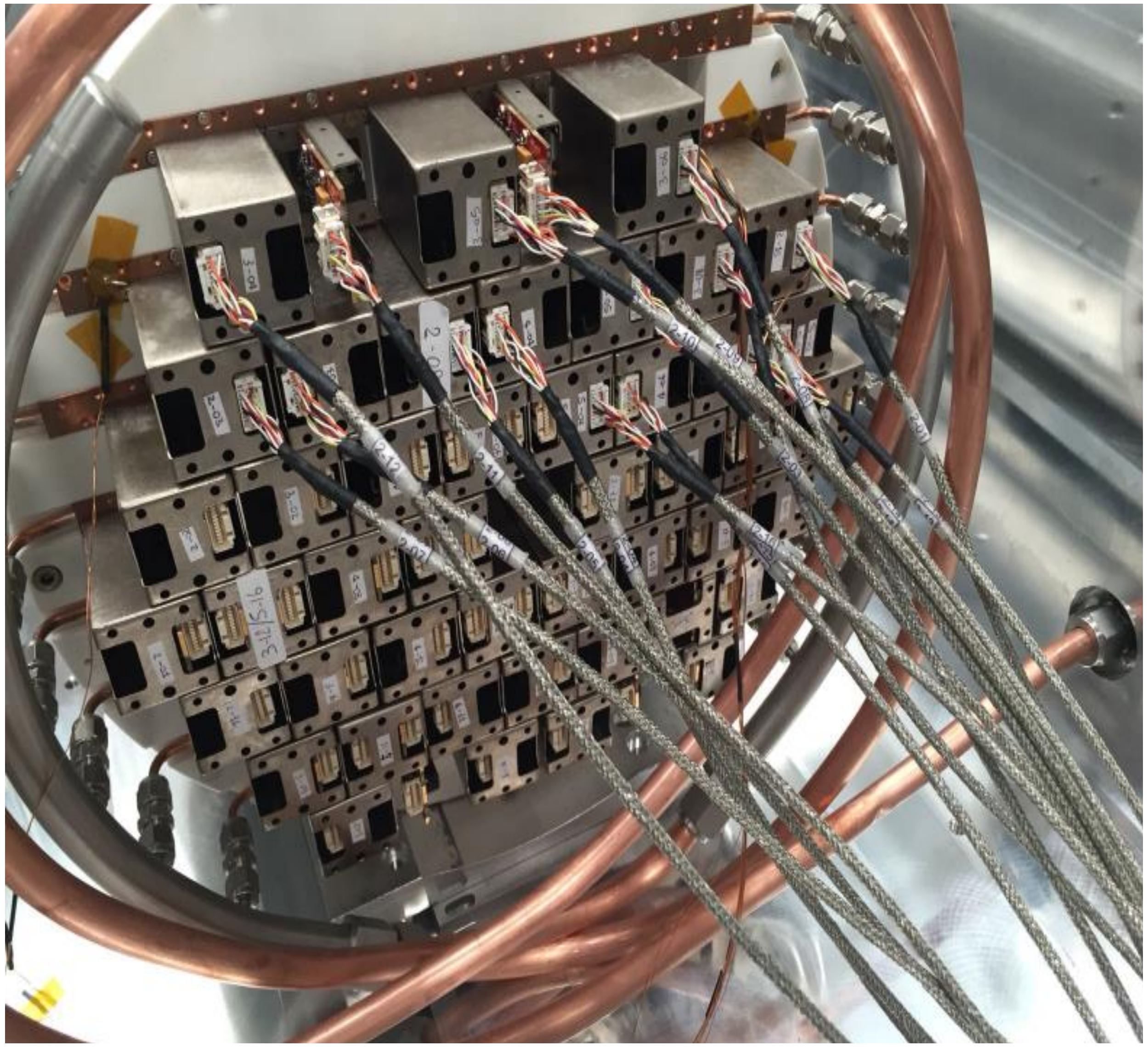




SiPM Holder

Calorimeter Prototype



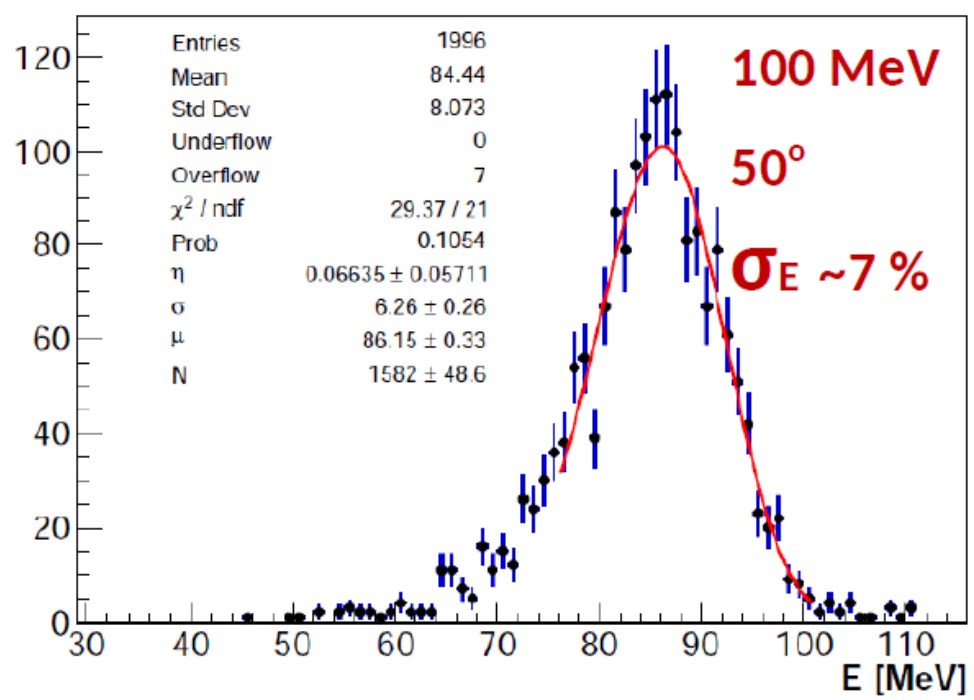


Calorimeter Prototype Test Beam

- May 2017 test beam with 70-115 MeV electrons at INFN Frascati
  - 51 30x30x200 mm^3 CsI crystals
  - Readout: Hamamatsu, SNESL, and Advansid SiPMs
- Results:

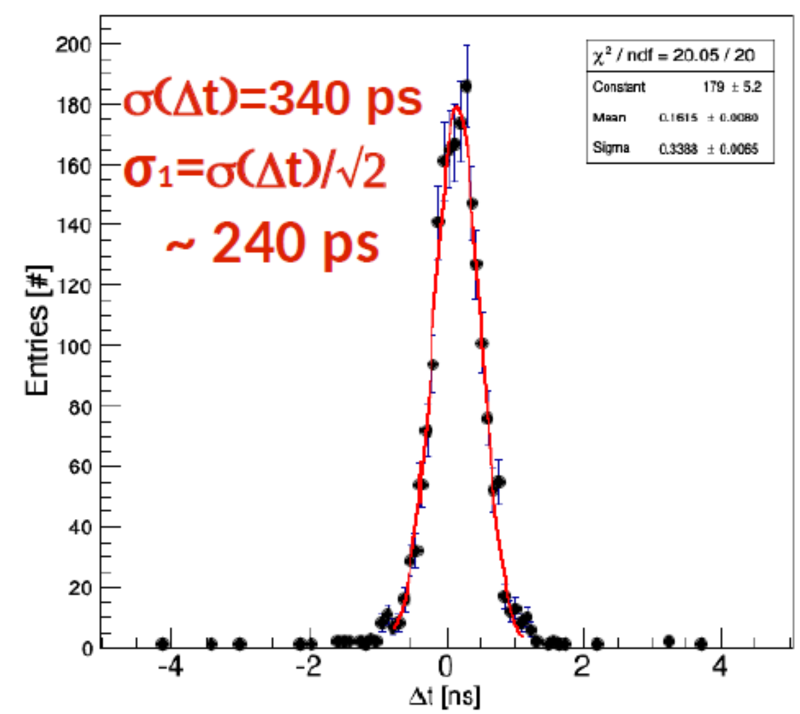
PM2018 – 14th Pisa Meeting on Advanced Detectors
https://agenda.infn.it/materialDisplay.py?contribId=444&sessionId=14&materialId=slides&confId=13450

Energy Resolution



Calibration with e$^-$ at 0°
For 100 MeV e$^-$ at 50°:
Energy resolution ~7%

Time Resolution



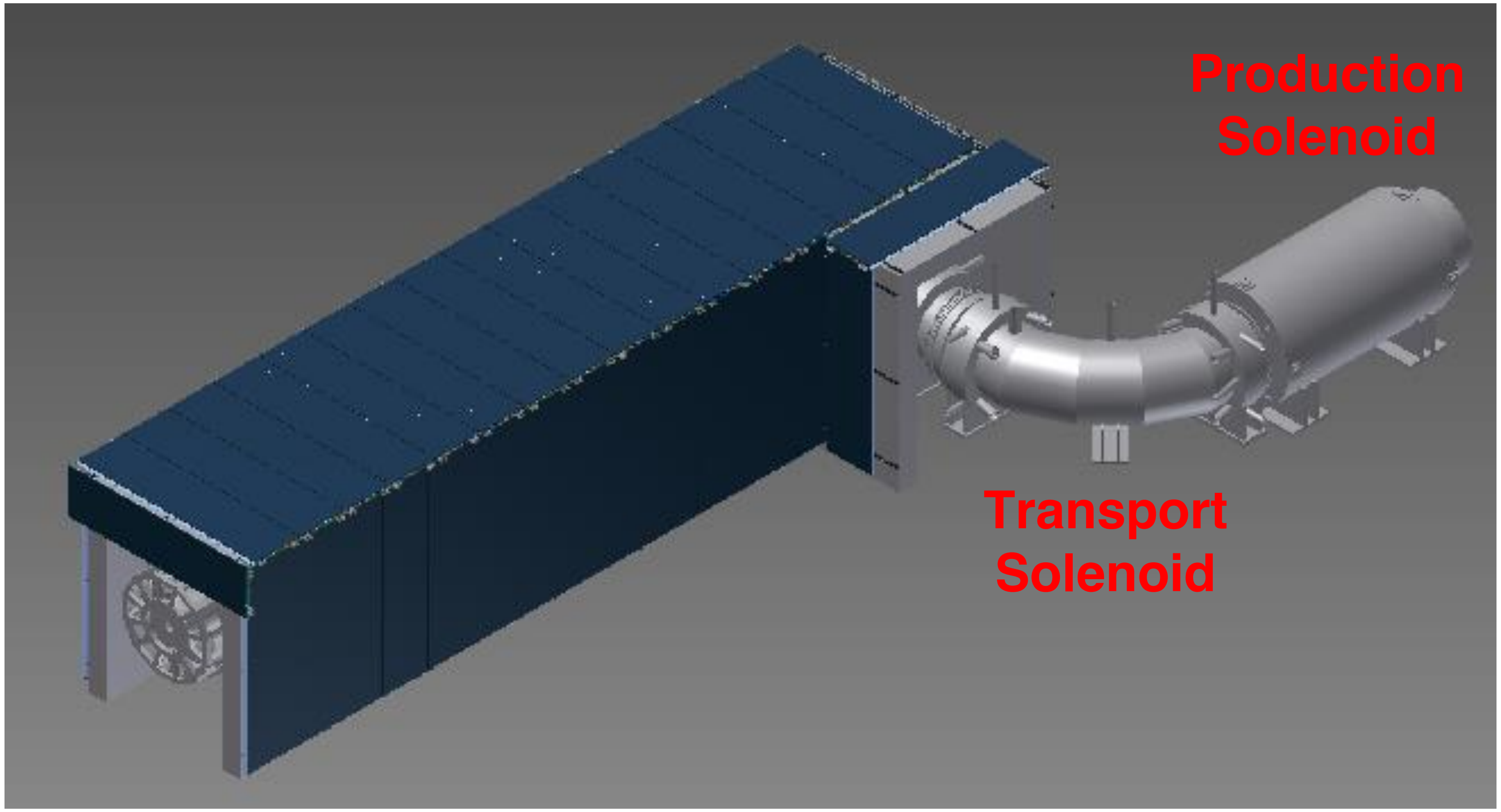
Δt: Time difference between two sensors reading the same crystal.

For 100 MeV e$^-$ at 50°:
Δt resolution ~340 ps
Single sensor resolution ~240 ps

- Energy and time resolutions satisfy our requirements (~10% and 500ps, resp.)

Cosmic Ray Veto I

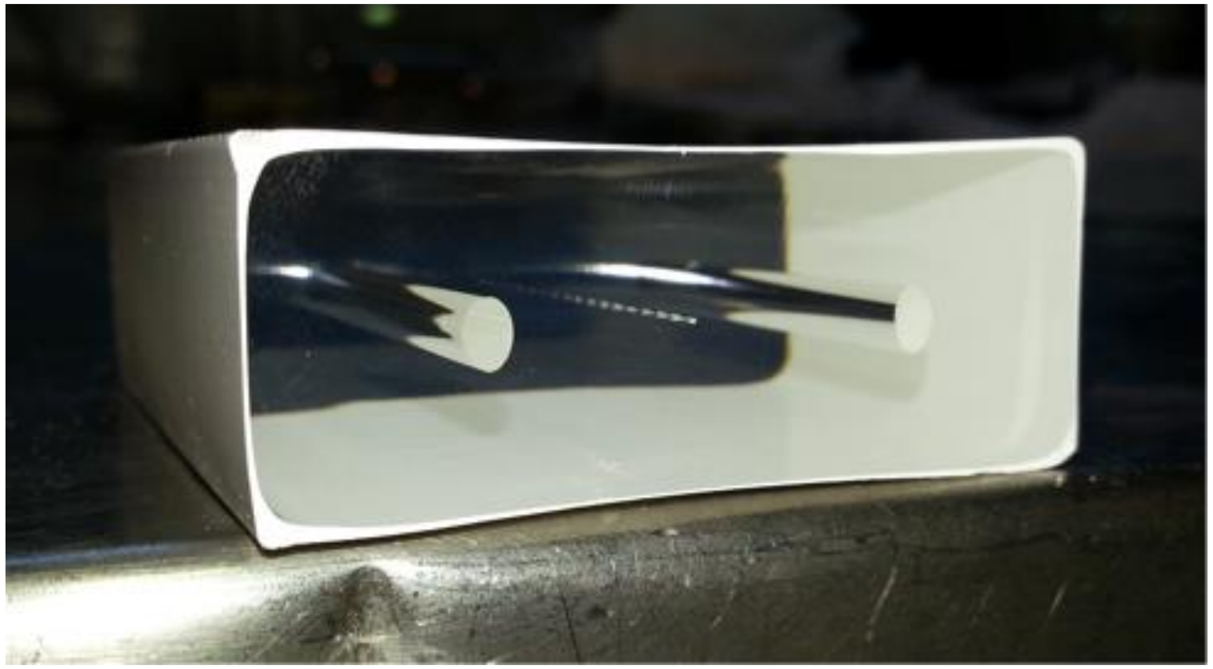
- The Cosmic Ray Veto (CRV) system surrounds the detector solenoid and half the transport solenoid
  - CRV identifies cosmic ray muons

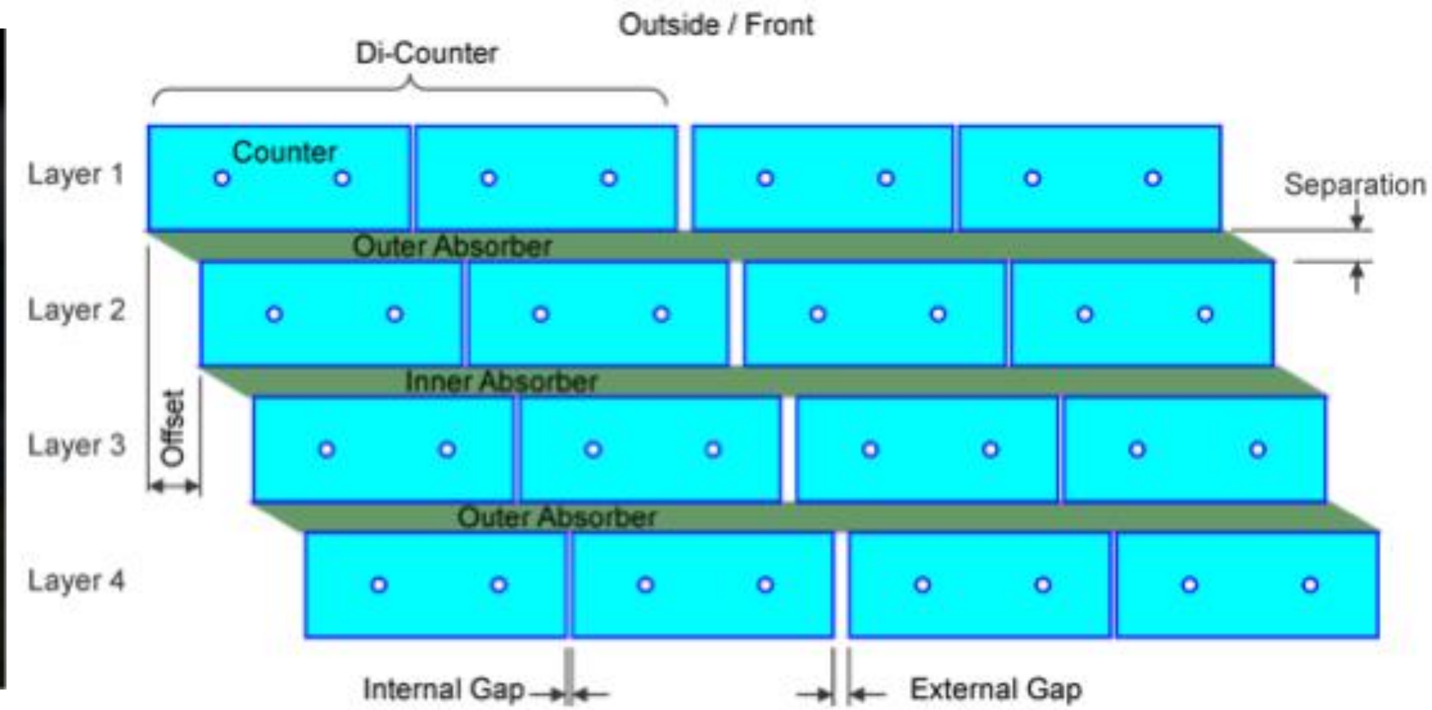


- Each day, ~1 conversion-like electron is produced by cosmic rays
  - Need the CRV to suppress this background

Cosmic Ray Veto II

- The CRV is composed of 4 layers of overlapping panels of extruded polystyrene scintillator

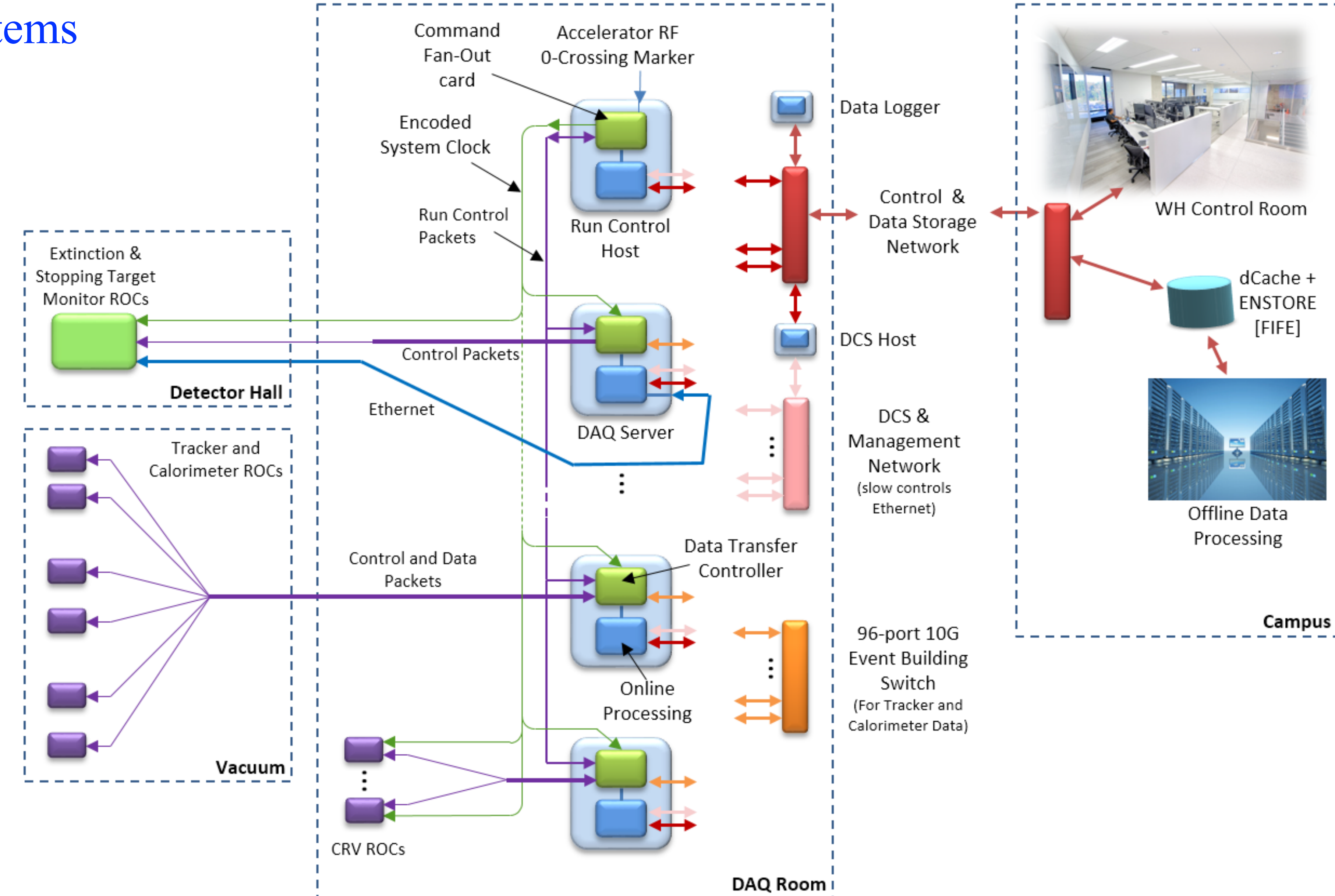




- Each panel is composed of 5 x 2 x ~450 cm^3 scintillator bars
  - 2 embedded wavelength-shifting fibers per bar
  - Both ends of the bars are readout by SiPMs
  - In testing, the veto achieves $\varepsilon > 99.4\%$ per layer

DAQ/Trigger

- Data Acquisition (DAQ) system provides readout and control for all the detector subsystems



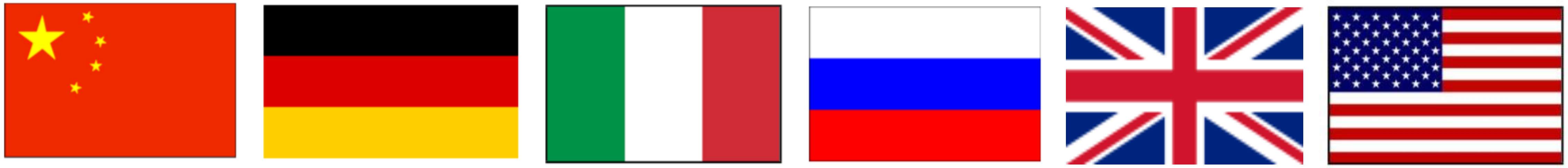
- Trigger processing is handled almost entirely in software (with some FPGA-based pre-processing)
  - Allows us to take advantage of commercial computing hardware
  - Filters designed and tested in the offline environment can be run in the online trigger environment

Mu2e Building

Mu2e

The Mu2e Collaboration

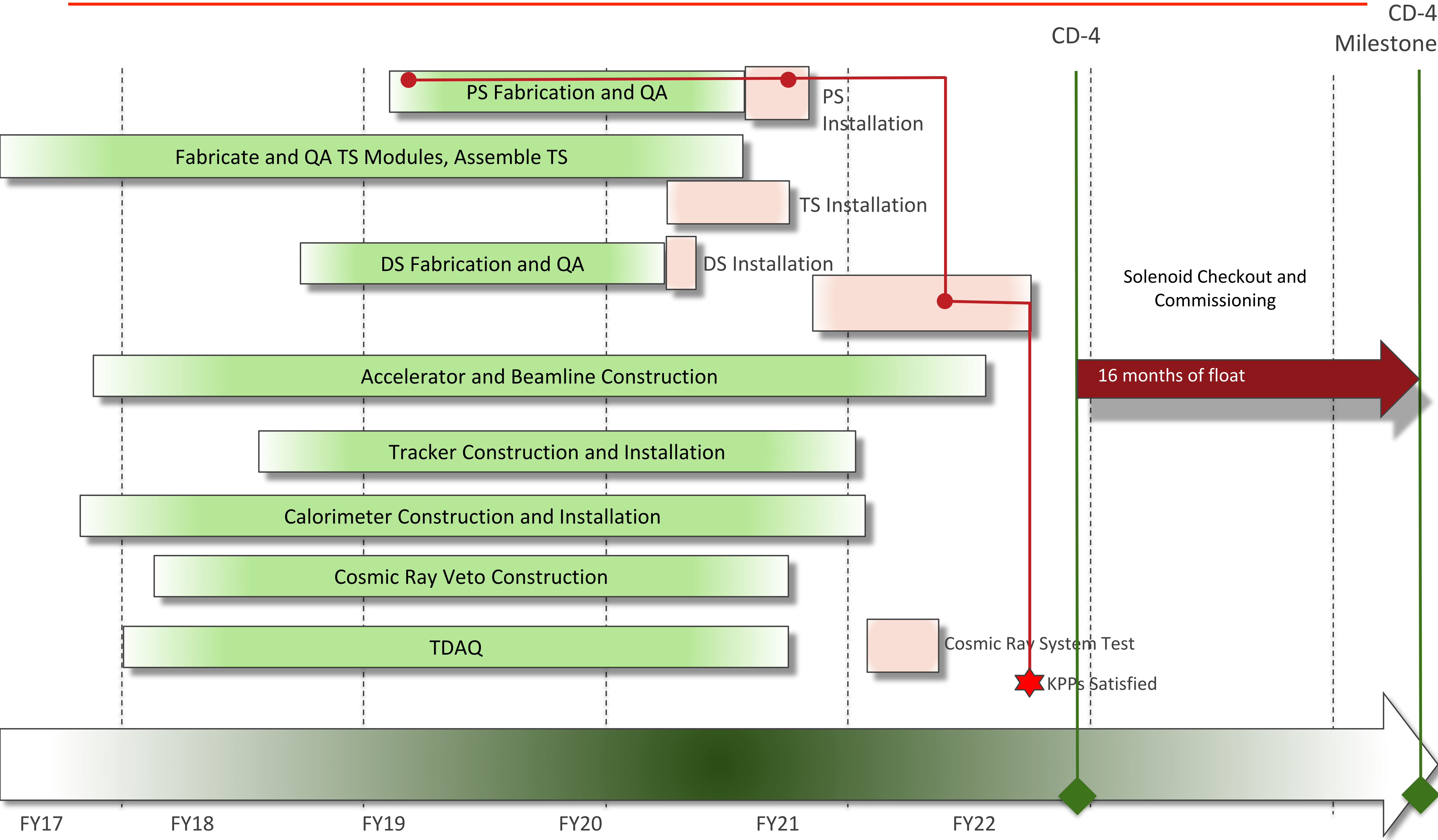
Over 200 Scientists from 37 Institutions



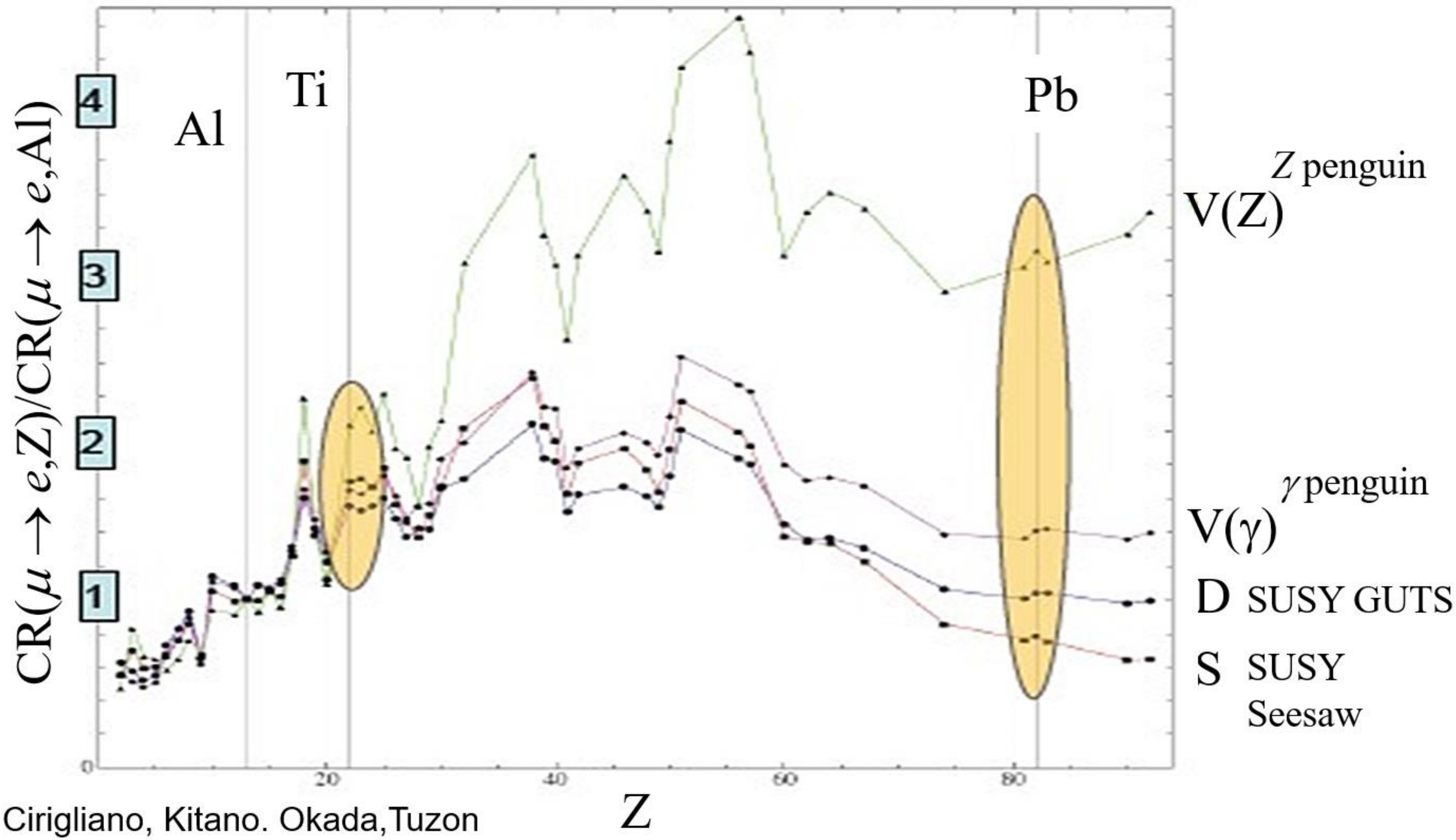
Argonne National Laboratory ● Boston University Brookhaven National Laboratory Lawrence Berkeley National Laboratory and University of California, Berkeley ● University of California, Davis ● University of California, Irvine ● California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna ● Duke University ● Fermi National Accelerator Laboratory ● Laboratori Nazionali di Frascati ● INFN Genova ● HelmholtzZentrum Dresden-Rossendorf ● University of Houston ● Institute for High Energy Physics, Protvino ● Kansas State University ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool ● University College London ● University of Louisville ● University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma ● University of Minnesota ● Institute for Nuclear Research, Moscow ● Muons Inc. ● Northern Illinois University ● Northwestern University ● Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● University of South Alabama ● Sun Yat Sen University ● University of Virginia ● University of Washington ● Yale University

Detector Hall (Lower Level)

Mu2e Schedule



Z-Dependence of $\mu \to e$ Conversion



Cirigliano, Kitano. Okada,Tuzon

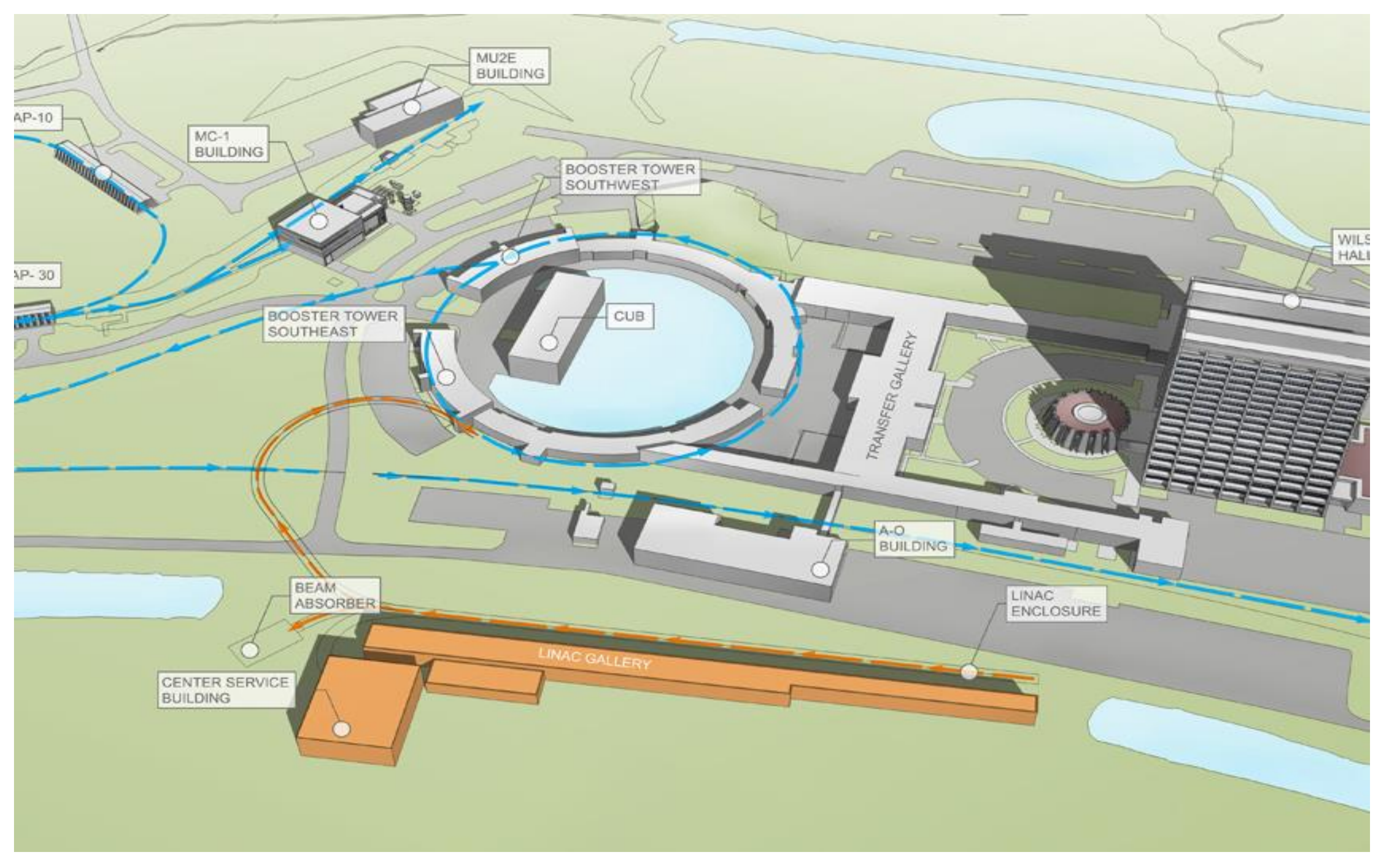
Lepton flavor violating mu – e conversion rate for various nuclei
M. Koike et al., J. Phys. G29 (2003) 2051-2054
DOI: 10.1088/0954-3899/29/8/401

Mu2e II Introduction

- As Mu2e approaches commissioning, we are also looking toward future upgrades
- The proposed Mu2e II experiment aims to achieve an order of magnitude improvement in sensitivity over Mu2e
  - If there is no signal at Mu2e: We could extend our sensitivity to find a signal or set new limits
  - If Mu2e does see something: We can improve our statistical significance and use different target materials to narrow down the NP processes involved
- To achieve a 10X improvement, we need:
  - An upgraded proton source (already approved)
  - Other upgrades to parts of the detector
- We aim to reduce costs by reusing parts of mu2e wherever feasible

Mu2e II Plans

- So far, various studies of Mu2e II backgrounds, sensitivity, and radiation damage have been performed
- A series of Mu2e II workshops has been held and the collaboration is involved in the Fermilab PIP-II planning process (a superconducting linac for LBNF and the muon campus)
    - PIP-II will have an energy of 800 MeV (Mu2e’s proton source is 8 GeV) which is below the anti-nucleon production threshold and will result in less background
- An expression of interest was recently submitted to the Fermilab PAC
- Timecale:
    - Mu2e is expected to run for 4 years of data-taking at full intensity
    - Assuming 2-3 years from the end of Mu2e to the start of Mu2e II, Mu2e II could begin taking data around 2030



Summary

- The Mu2e experiment will improve current $\mu^- N \rightarrow e^- N$ CLFV sensitivity limits by 4 orders of magnitude (and thereby constrain many NP models at mass scales up to ~10,000 TeV)

- Mu2e will be sensitive to a broad range of NP models
    - If we see a signal, switching to another stopping target material will provide further information about the Lorentz structure of the NP

- Progress is on schedule and we plan to begin commissioning in 2020

Backup Slides

Example CLFV Processes

- Potential channels for CLFV searches:

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 x 10^{-8}	
$\tau \to \mu\gamma$	BR < 6.8 x 10^{-8}	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 x 10^{-8}	
$\tau \to eee$	BR < 3.6 x 10^{-8}	
$K_L \to e\mu$	BR < 4.7 x 10^{-12}	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 x 10^{-11}	
$B^0 \to e\mu$	BR < 7.8 x 10^{-8}	
$B^+ \to K^+ e\mu$	BR < 9.1 x 10^{-8}	
$\mu^+ \to e^+\gamma$	BR < 4.2 x x 10^{-13}	10^{-14} (MEG Upgrade)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 x 10^{-12}	10^{-16} (Mu3e)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 x 10^{-13}	10^{-17} (Mu2e, COMET)

- Although CLFV τ processes could have larger branching ratios than μ processes, dedicated muon experiments can produces $O(10^{10})$ μ/s whereas colliders produce $O(10^{10})$ τ/year

Mu2e Discovery Potential

- Mu2e has discovery sensitivity across a wide range of models:

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

arXiv:0909.1333[hep-ph]

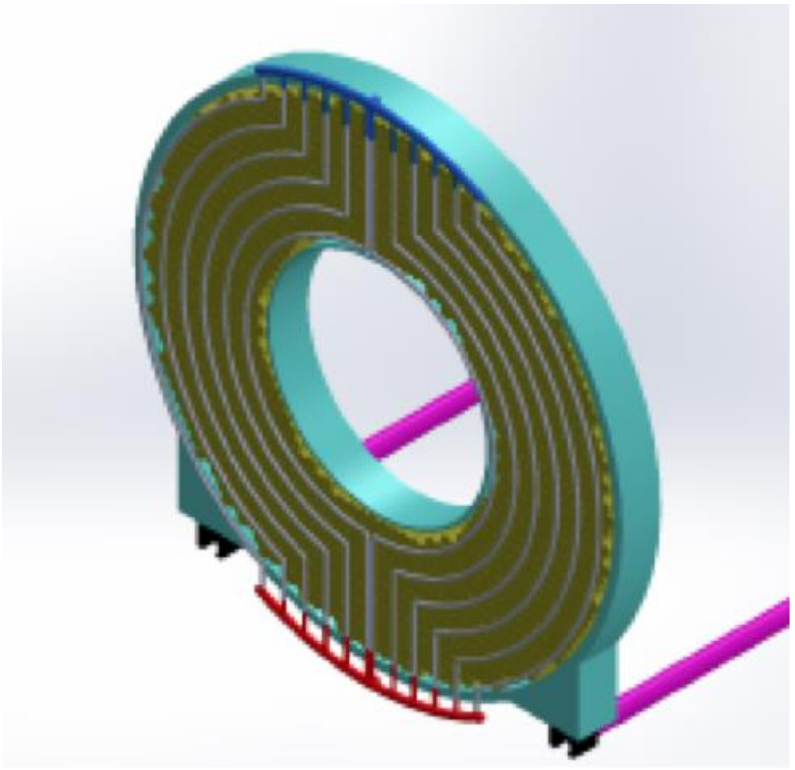
★★★= Discovery Sensitivity

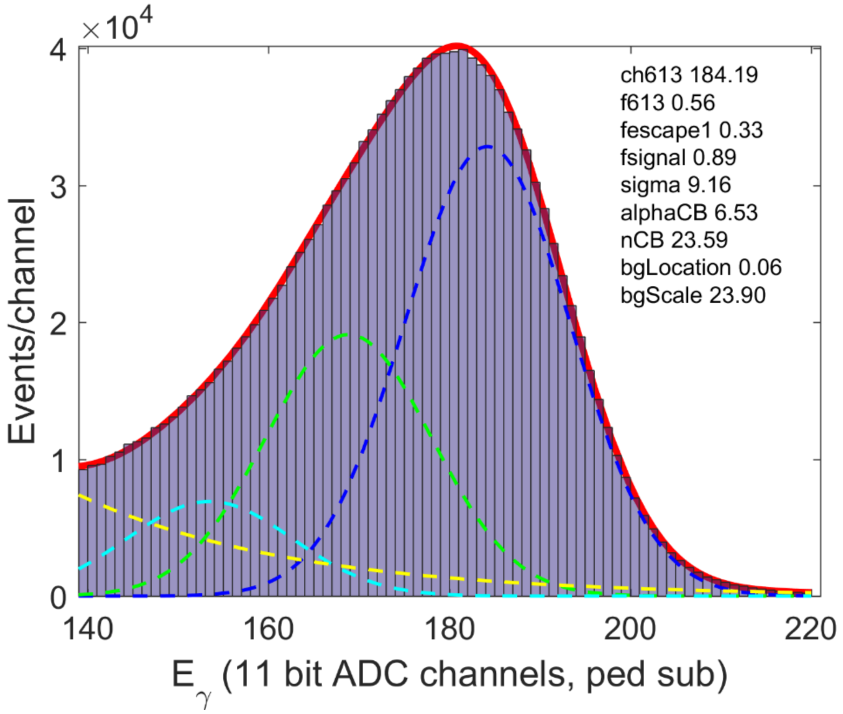
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

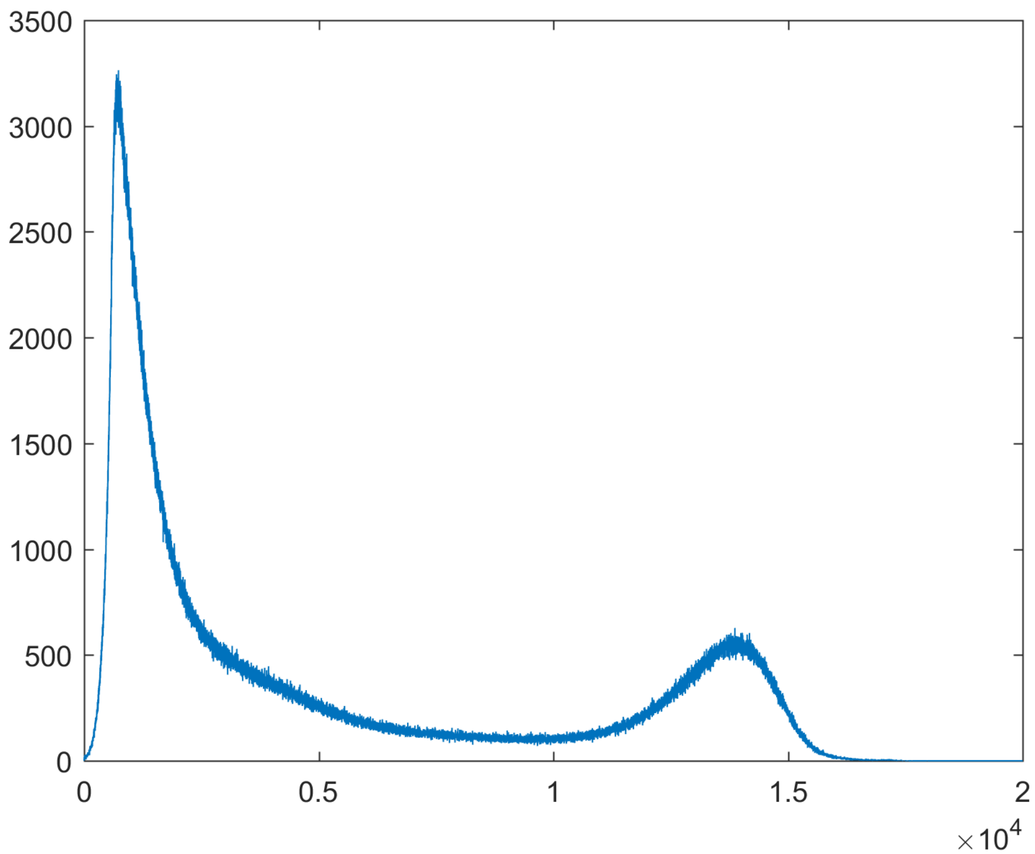
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Calorimeter Calibration

- The calorimeter will be calibrated using activated Fluorine-rich fluid
  - Fluorinert is activated using neutrons from a DT generator
  - Fluid is pumped through pipes in front of the disks
  - Calibrate energy scale to < 0.5% in a few minutes
- A UV laser system will continuously monitor SiPM gains
  - Distribute light using silica optical fibers



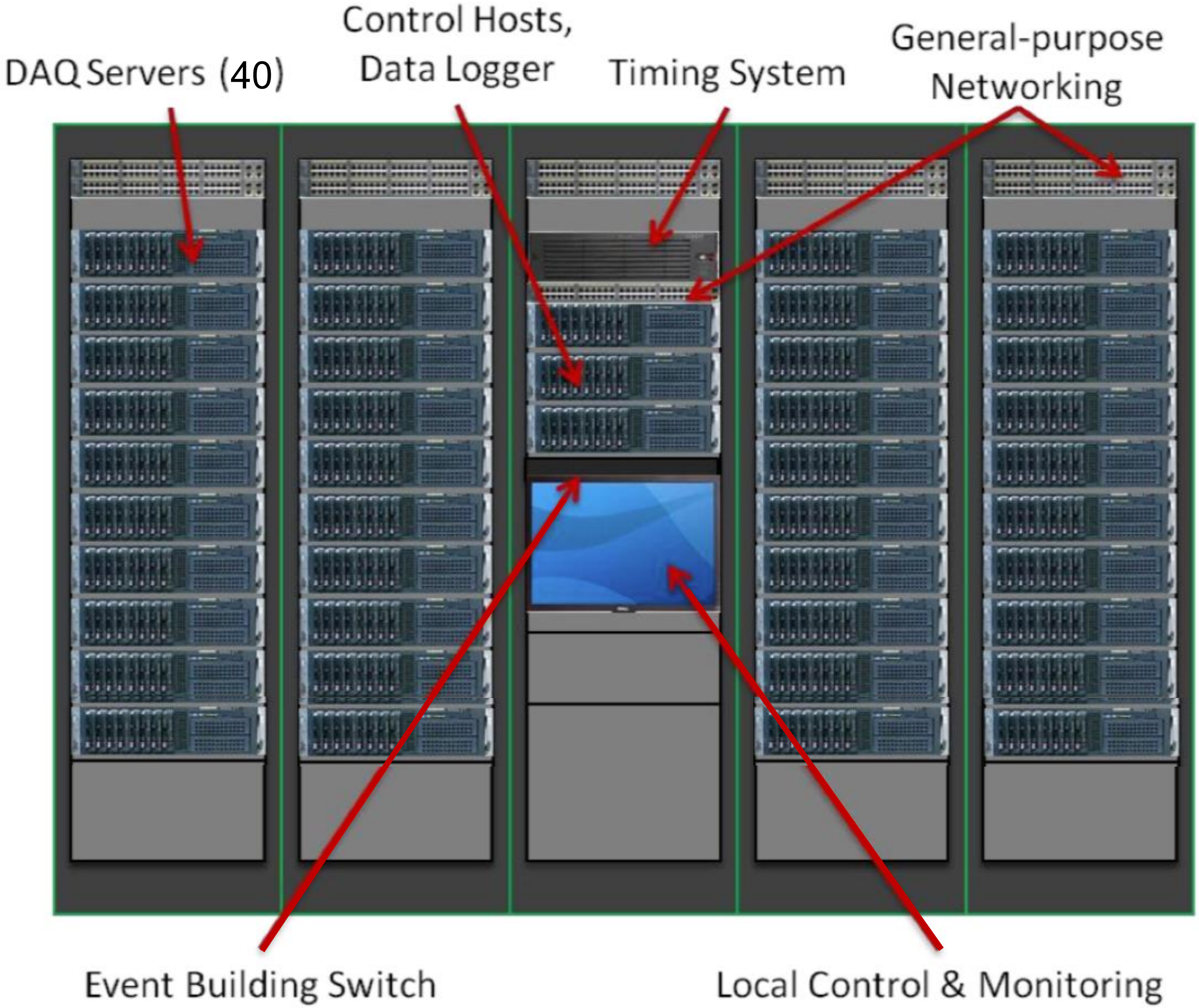




Prototype Spectrum

DAQ Server Setup

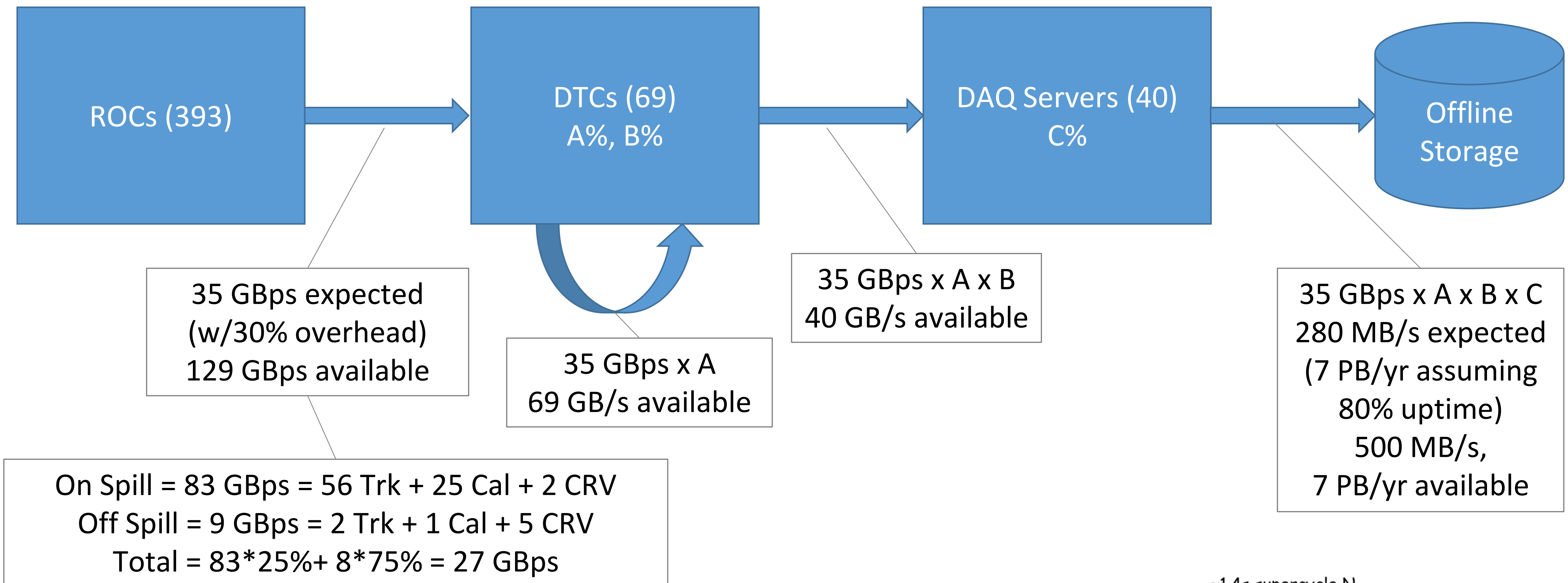
- Online processing provided by 40 commercial 3U rack-mount servers
- Each server houses 1 or 2 PCIe cards with onboard FPGA and custom firmware that provide detector readout/control as well as data pre-processing



Average Data Rates

pre-event building fraction pass: A
Level 0 pre-processing fraction pass: B
Level 1 Filter fraction pass: C

Total Required Rejection Ratio: ~125:1



- Requirement: Process 200k events/s
  - Therefore, trigger algorithm must run in:

$$1 / 200K \frac{events}{s} * 40 \text{ nodes} * 20 \frac{art\ threads}{nodes} = \mathbf{4.0} \frac{ms}{\frac{events}{art\ threads}}$$